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APPLICATION OF NUMERICAL OPTIMIZAITON TECHNIQUES TO SURFACE COMBATANT DESIGN SYNTHESIS

by

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APPLICATION OF NUMERICAL OPTIMIZATION TECHNIQUES TO SURFACE COMBATANT DESIGN SYNTHESIS

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ABSTRACT

This thesis presents the effort to incorporate a numerical optimizer into an existing ship design synthesis math model. The goal is to improve the functionality of the model while retaining the intrinsic value of the model's friendly user interface, which is greatly advantageous for its use as a learning tool. A description of the math model and its origin and intent are presented along with a discussion of numerical optimization techniques and tools. The integration and linking software is described along with the actual Integrated Ship Design System. Results of comparison and sensitivity studies are also presented.

TABLE OF CONTENTS

LIST OF FIGURES

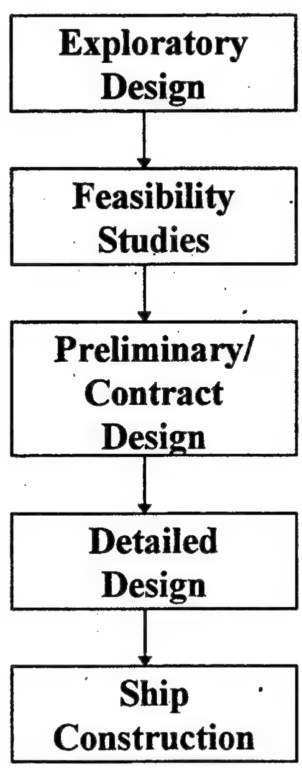
LIST OF TABLES

I. INTRODUCTION

A. BACKGROUND

The process of designing a modern combatant ship is an exceptionally complicated and intricate undertaking. The challenge of the ship designer is to engineer a total ship system that fulfills rigorous requirements within certain constraints, such as the laws of nature, the limits of technology and especially in today's environment, limited budgets. This requires the ship designer to have an in depth knowledge of numerous engineering disciplines and possesses a special ability to bring together or synthesize these diverse areas to create a balanced ship design.

The ship design process can be divided into several phases, each which increases in detail and resource expenditure as the process proceeds;



A successful ship design starts with a set of operational requirements generated by the end user. These requirements typically include a nominal mission profile and payload specifics (i.e. combat systems). The next step requires defining the initial concepts for the overall ship configuration. While the operational requirements may dictate a specific ship type (i.e. an oil tanker should be a monohull to maximize cargo capacity), the surface combatant can take on many forms (monohull, multihull, wave piercer, etc.), each of which may have advantages and disadvantages but still fill the mission need. The same is true for the propulsion system; numerous permutations may meet the requirements, but the designer must choose wisely to produce the most balanced design. This leads to the implementation of feasibility studies, the objective of which is to conduct trade-off studies between capabilities, cost and risks which are then presented as whole-ship solutions. The whole-ship solution consists of the hull form type, its gross characteristics such as beam, draft, length, a gross cost estimate and the areas of major technical risk. These whole-ship solutions come about through the use of a traditional iterative design spiral as shown in Figure 1. It is the improvement of this portion of the design process that is the focus of this thesis. The remainder of the design process is dedicated to refining the chosen design(s) and completing detailed engineering studies that eventually lead to the production of the ship [Ref. 1].

It is during the feasibility study phase of the design process that having an ability to examine many different designs in a rapid, but consistent manner is highly desirable. A multitude of variables must be considered and evaluated using proven techniques that have been developed and refined through years of use. Sophisticated computer aided combatant ship design tools have been extensively developed over the years. The primary system

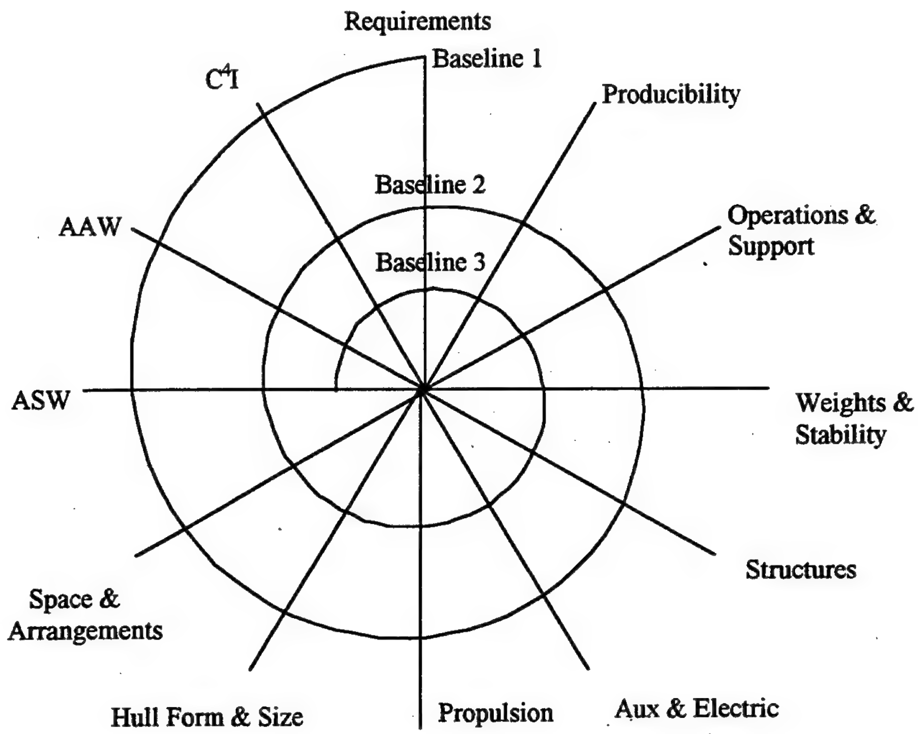


Figure 1. Iterative Ship Design Spiral [Ref. 1].

being used by the U. S. Navy is the Advanced Ship System Evaluation Tool (ASSET) [Ref. 2]. But for the student, these design tools are really too far removed from the basics needed to learn and understand the fundamentals of ship design.

Efforts at the Department of Ocean Engineering at the Massachusetts Institute of Technology in the 1970s produced several naval combatant ship synthesis models. Those developed by Reed [Ref. 3], and Graham and Hamly [Ref. 4] are particularly relevant in that they form the basis of the model used in this thesis. The Simplified Math Model for the Design of Naval Frigates was adapted from these original models and has been revised several times throughout the years to add additional features and to keep pace with rapidly changing software. The model in its current form is written in Mathcad, which presents an

easy to read and understand object oriented environment for equations, while maintaining powerful evaluation capabilities.

B. OBJECTIVES

The simplified math model generates the basic data for a first order design, though it requires the designer to check manually and adjust numerous parameters to ensure they fall within the feasible range designated within the model. It is then up to the designer to choose what parameters to change if the results are infeasible, and this can lead to extended or fruitless searches in the wrong direction. To aid the designer in more rapidly reaching a reasonable design, it is possible to use the techniques of numerical optimization to drive the model to the best design for a given specific objective and set of constraints. For example, the designer may wish to minimize the displacement of a ship given a fixed payload, and that the principle dimensions (beam, draft, length) are constrained so that the ship will fit into existing dry dock facilities. The objective function becomes the mathematical expression for displacement, which must be minimized such that it does not violate the constraints placed on beam, draft, and length. This approach has an added benefit that it aids the student in understanding what variables and constraints control the design.

The use of numerical optimization is not new in the realm of ship design, and the literature records numerous efforts to incorporate optimization techniques stretching back to the 1960s. MIT demonstrated early leadership in the efforts to apply the methods of numerical optimization to practical ship designs. Chryssostomidis [Ref. 5] investigated commercial containership preliminary design, choosing a least cost criterion as the optimization goal. His study found that payload (i.e. cargo) volume and weight were

driving the overall operational costs, and his optimization of design focused on the development of vessels designed to the discrete sizing of shipping containers.

This type of study lent itself well to the easily quantifiable economic factors considered in the design of single-purpose commercial ships. Optimizing economic factors alone for multi-mission naval vessels on the other hand, is not so easily done due to the difficulty of quantifying missions that are not of an economic nature. Holmes [Ref. 6], and Wagner [Ref. 7] attempted to apply the least cost criterion to the design of a naval auxiliary and salvage tug. They found that military mission effectiveness cannot be readily measured in economic terms unless each ship's missions are completely specified. Also a numeric value for effectiveness must be applied and remain consistent when selecting between different designs.

These early efforts to apply optimization to ship design shared a common optimization technique, the exponential random search method, developed by Mandel and Leopold [Ref. 8]. It is essentially a brute force method that randomly generates guesses within the constrained design space for the design variables, and computes the objective function and compares it to the previous value. If the new value is less that the old, the new value replaces the old and the process is repeated until convergence. Development of more sophisticated optimization algorithms in the 1980s permitted further applications to ship design.

Jenkins [Ref. 9] applied the COPES/CONMIN optimization program developed by Vanderplatts [Ref. 11] to the Reed Ship Synthesis Model [Ref. 3]. This optimization program utilized more advanced techniques such as the method of conjugate directions for locally unconstrained problems and the method of feasible directions for the locally

constrained problem [Ref. 10]. The use of this sophisticated code permitted more rapid convergence of the ship synthesis program, which fulfilled the goal of allowing more designs to be considered during the preliminary design phase.

Improving the functionality of the MIT Simplified Math Model by adding an optimization capability is the central challenge of this research effort. The objective then, of this thesis is to incorporate proven numerical optimization tools into the MIT Simplified Math Model and have the system deliver an optimal and reasonable design under various payload conditions.

C. COMPUTER PROGRAM OVERVIEW

To successfully meet the objective requires the integration of several distinct computer modules, each in its own computer language, which alone cannot communicate with each other. The ship's payload data is generated using an Excel spreadsheet, the Simplified Math Model uses Mathcad to evaluate the ship design and the numerical optimizer is a Matlab program. To enable these disparate modules to pass data among themselves in a logical and meaningful manner, an integration and linking program called MathConnex is utilized. Through the use of MathConnex, all the necessary design variables can be generated, passed between modules and selected results displayed, all while remaining in a consolidated and user friendly work space. A MathConnex representative overview of the computer program is shown in Figure 2.

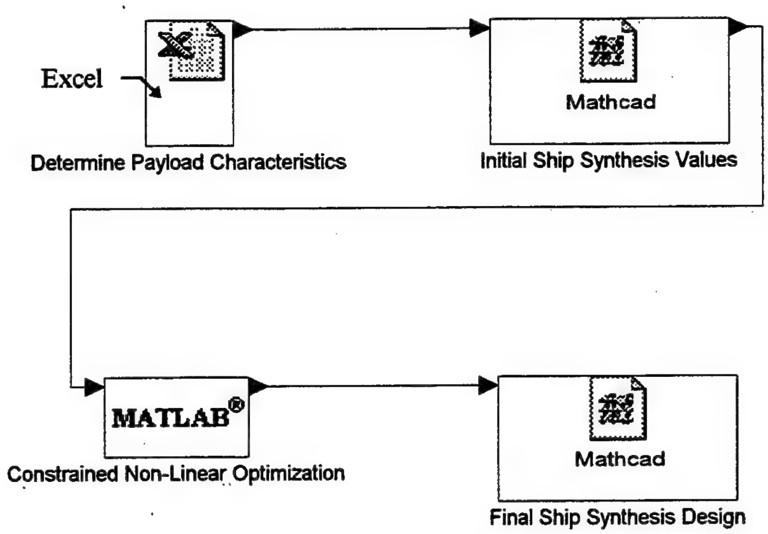


Figure 2. MathConnex Computer Program Overview.

II. MIT SIMPLIFIED MATH MODEL

A. ORIGIN AND INTENT

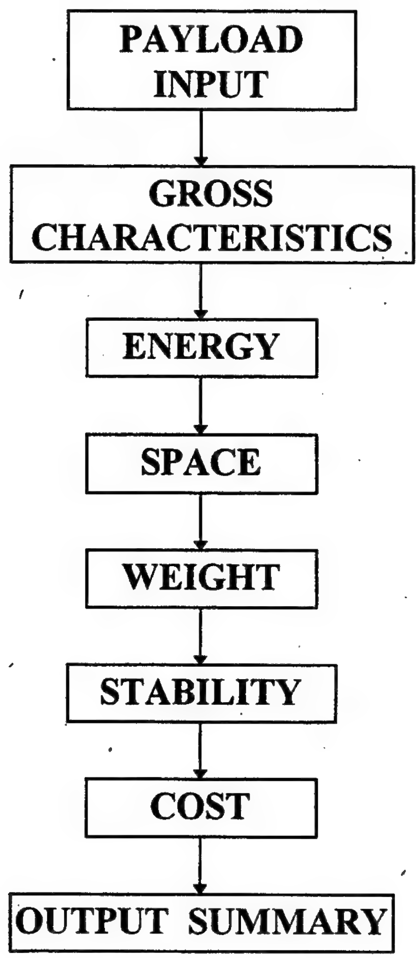
In the past, students of naval engineering were required to wade through pages of hand calculations, and stacks of tables and charts, (examples are contained in the Appendix C which are part of the Math Model documentation), to complete each iteration in the ship design spiral. The modern personal computer presents a means by which some of the drudgery can be eliminated while still providing a meaningful learning experience. The Department of Ocean Engineering at the Massachusetts Institute of Technology (MIT) has spent the past two decades developing a simplified math model for ship design. The current model traces its origins to the work completed by Reed [Ref. 3], which in turn drew heavily upon the Navy's destroyer design model, DD07, and the Center for Naval Analyses Conceptual Design of Ships Model (CODESHIP) developed in the 1960s. Since the personal computer has become ubiquitous and more powerful, the model has been converted from a main frame environment and major revisions have continued to be made to keep pace with hardware and software developments throughout the 1980s and 1990s.

The model is the central design tool utilized in the Principles of Naval Ship Design course offered at MIT. In its current form, the model is presented in a programming language called Mathcad [Ref. 13], which displays equations and relations in an easy to read object oriented format, while still performing high powered mathematical calculations. The visual interface allows students to work through problems as they would on a sheet of paper, but they can easily vary different parameters and quickly see the impact on the design, while not getting bogged down in routine calculations. This

allows more designs to be evaluated, and the student gains a greater appreciation for the ship design process.

B. PROGRAM DESCRIPTION

The Mathcad display of the model is very easy to read and understand, since it looks just like a sheet of equations, with actively updated graphs, tables and a summary of output. Mathcad reads from left to right, and from the top to bottom of the page, which allows the model to be organized according to the following macro flow diagram.



Most of the user-supplied payload data is generated using an Excel spreadsheet which contains weight, center of gravity, area and electrical power requirements for

current and near future surface combatant systems. Additional inputs such as crew size, type of power plant and speed requirements are generated by the user and all this data is then manually input to the model. The gross characteristics of the ship are then generated using the form coefficient values and displacement, which are varied by the user in the output summary section . Energy requirements for propulsion and electrical service load are calculated to ensure the installed power plant is sufficient and to provide the fuel weight and volume for the given endurance. Area, volume and weight calculations for the rest of the ship follow. Finally, the static, intact stability is calculated and a simplified cost model generates the lead ship cost.

The model's summary section contains the ship design form coefficients that are set by the designer. These coefficients are limited in range due to the constraints imposed when using Taylor Standard Series hull resistance data [Ref. 12]. There are four coefficients that are manipulated by the designer; the Prismatic Coefficient C_P, the Maximum Transverse Section Coefficient C_M, the Beam-to-Draft Ratio C_{BT}, and the Displacement-to-Length Ratio $C_{\Delta L}$. These coefficients are assigned as global variables and fix the basic characteristics for the design being considered. The model uses these fixed values along with a designer-provided estimate of the displacement, W_{FL}, to generate values for the beam, draft, and length, which in turn generates a new displacement, W_T.

To initiate use of the model, all the user-supplied data is input in the first section and in the output summary page. For the first iteration, the displacement is calculated assuming the payload weight is ten percent of the full load displacement and is entered in the summary page as W_{FL}. The model then generates a new displacement, W_T which is compared to the previous displacement, W_{FL}. After each iteration, several values in the

model must be checked to ensure the design is valid, and these are highlighted by the double pound sign (##) in the right margin. If all the checks are satisfactory, the next iteration is completed by changing W_{FL} to the value in W_T. Once the displacement error is sufficiently small, usually around one percent, and the checks throughout the model are satisfactory, the model has converged. If the values to be checked in each iteration are not satisfactory, then the designer must change one or more of the variables to bring the design into compliance. The form coefficients are the variables that are manipulated for a fixed payload, and it is here that the student can best see the impact of these on the overall design. Once a form coefficient is altered, the design iteration process is repeated until convergence is reached. A detailed model description containing the symbol lists and micro flow diagrams is contained in Appendix C.

C. LIMITATIONS AND MODIFICATIONS

The model clearly fills its intended purpose of providing an easy to use and understand design tool for the student of naval engineering. It requires the designer to pay close attention to the details of each iteration, preventing a "black box" mentality where numbers are input in one end and get spit out the other, without knowing what really goes on in between. The drawback is that all this manual manipulation does not lend itself to the inclusion of a numerical optimizer, which by definition must search through the entire design space and is iteration intensive. If each iteration required the designer to manually check for compliance within the design variable constraints, the optimization process would be agonizingly slow and its use would be deterred.

To best leverage the advantages of the model in conjunction with the optimizer and the payload generation spreadsheet, the transfer of data between them must be

improved. The MathConnex program fills the very well. MathConnex provides the channels through which the data flows between the different applications using simple variable designators and click-and-drag connections. The Mathcad model was modified so that the entire payload is automatically loaded from the Excel spreadsheet each time the model is run. Likewise, the values of the design variables generated by the optimizer are passed back into the model for the final design synthesis.

One of the checks required in the model is to ensure that the depth at the midship station, D_{10} is greater than the minimum calculated for the sheer line (see Section IV of the model). This was modified so that D_{10} will always be one foot larger than D_{10min}, thus ensuring compliance with the sheer line criterion. The remainder of the model remains in its original form.

III. NUMERICAL OPTIMIZER

A. OPTIMIZATION THEORY AND TECHNIQUES

The desire to provide the best solution to a design problem has always been a primary goal of designers. As our engineered systems have increased in complexity, producing just a feasible design can require significant effort. With the advent of the high speed computer, numerical mathematical methods have evolved that permit the designer to produce not only a feasible design, but through proper application of these mathematical methods, the designer can find the best or optimal solution to the problem with little additional effort.

For proper analysis, the design problem must be posed in a manner consistent with typical numerical optimization methods. A widely accepted form for a nonlinear constrained optimization problem is presented by Vanderplatts [Ref. 10];

Minimize:	$F(\mathbf{X})$		objective function
Subject to:	$g_j(\mathbf{X}) \leq 0$	$j=1,m$	inequality constraints
	$h_k(\mathbf{X}) = 0$	$k=1,l$	equality constraints
	$X_i^l \leq X_i \leq X_i^u$	$i=1,n$	side constraints
	$\mathbf{X} = \{X_1\ X_2\ X_3 \ldots X_n\}$		design variables

The vector **X** contains the minimum number of design variables that describe the system to be optimized. The objective function is the relationship that expresses the interdependence of the design variables and is the function to be optimized. The constraint functions, explicit or implicit functions of the design variables, limit the design space that is searched to ensure feasibility of the solution. It should be noted that these functions and their first derivatives must be continuous in **X**.

Nonlinear constrained optimization requires the use of sophisticated algorithms which for the purposes of this research are described in detail in the Matlab Optimization Toolbox Handbook [Ref. 14]. It is worthwhile, though, to investigate a simple constrained optimization problem to demonstrate the basic concepts in the hope of creating a better understanding of the larger problem.

As a hypothetical example, consider the two dimensional problem using the ship's beam (B) and draft (T) as the design variables. The side constraints require the beam to be greater than 30 feet but less than 70 feet, and the draft greater than 10, but less than 30 feet. An inequality constraint uses the beam to draft ratio, which is no less than 2.8 and no greater than 3.7. In the standard form the problem would be expressed like this;

Minimize:	F(B,T)	objective function
Subject to:	$2.8 \leq B/T \leq 3.7$	inequality constraint
	$30 \leq B \leq 70$	
	$10 \leq T \leq 30$	side constraints
	$\mathbf{X} = \{B \;\; T\}$	design variables

The objective function can be any continuous function of the design variables B and T. This usually represents some characteristic of the ship, such as displacement, cost, or payload fraction, which is to be optimized. The constraints bound the region of the design space and control the search so that only feasible solutions are returned. An unconstrained search might return the mathematical minimum as a negative displacement, which is obviously is infeasible. Figure 3 defines the design space, and it is easy to see that the feasible range for the objective function is contained within the outlined area and that the optimal minimal value is unique. This graphical representation clearly shows the

location of the optimum, but most design problems are much more complex and do not lend themselves to such an easy solution. As complexity of the design space increases, the only reasonable means to solve the optimization problem lies in the use of numerical methods.

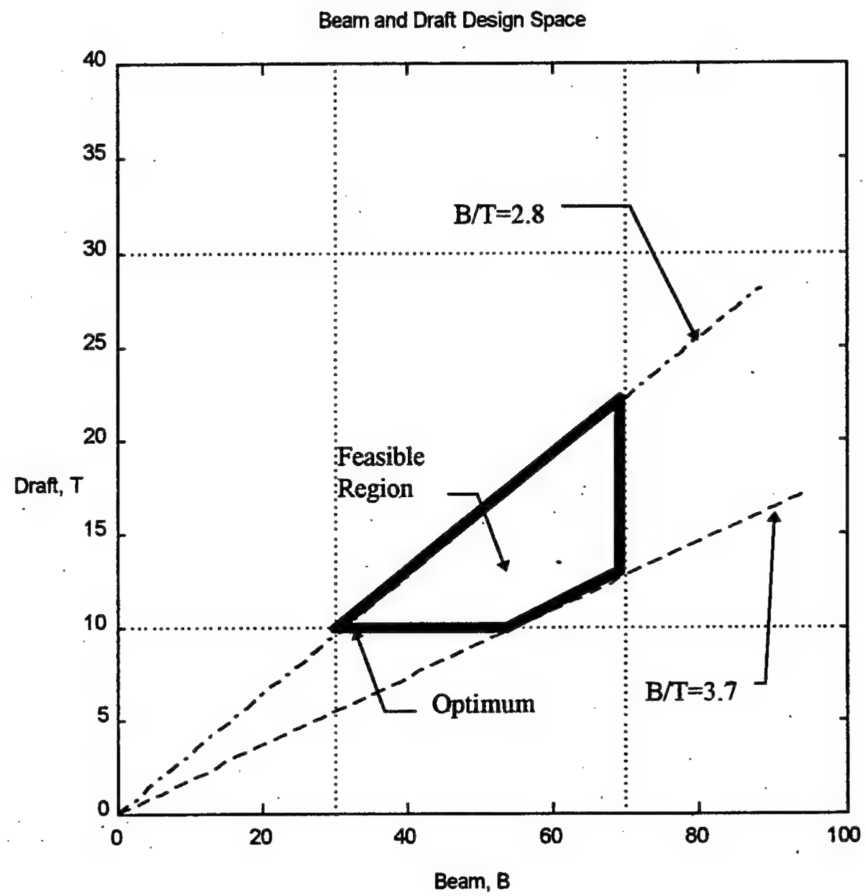


Figure 3. Two Dimensional Design Space

The optimization problem requires a sequential search of the design space to find the optimum, and this causes the process to be iterative by nature. The problem can then be reduced to two remaining tasks; find in which direction to search, and how big a step to take in that direction. The iterative form is then defined as;

$$\mathbf{X}^{q} = \mathbf{X}^{q-1} + \alpha^{*}\mathbf{S}^{q}$$

where q is the iteration number, **S** is a vector search direction, and α^* is a scalar that defines the step size of the move in the direction **S**. The search direction must be chosen so that it will reduce the objective function while not violating any constraints. The step size must be appropriately chosen so that the problem converges efficiently but accurately. The core remainder of optimization theory is therefore concerned with the details of choosing the best search direction and step size. References 10 and 14 provide in-depth discussion and analysis on this and many other optimization topics. Reference 14 is particularly helpful in describing the algorithms used within the Matlab optimizer.

B. MATLAB OPTIMIZER DESCRIPTION

Matlab invokes the constrained nonlinear optimizer by using the command "constr". The problem is posed in the standard form and is input into Matlab in the following format;

x = constr('function',x0,options,vlb,vub,[ ],p1,p2...)

- x is the vector of returned optimized design variables.
- 'function' is the M-file containing the objective function and constraints.
- x0 is the initial guess of the design variables.
- options controls output displays and termination criteria.
- vlb/vub are the upper and lower boundaries on the design variables or the side constraints.
- p1, p2 are additional variables to be passed into the 'function' M-file.

The 'function' M-file must be properly formatted to work with the optimizer;

function [f,g]=function name(input variables)

- f is the value of objective function.
- g is the value of the constraint vector.

C. OPTIMIZER FUNCTION DESCRIPTION

1. Objective Function

The choice to use full load displacement as the objective function was reached by weighing several factors. Previous optimization studies provided very good rationale for using displacement as the objective function when designing surface combatants [Ref. 9]. Additionally, the calculation of the displacement requires the use of all the major modules within the math model, which have subsequently been incorporated into the Matlab optimizer as function M-files. This will ease future research by allowing use and modification of existing function M-files and permitting them to be tailored to calculate different objective functions.

2. Design Variables

The choice of design variables is derived from the choice of the objective function. A close study of the math model uncovered that all the derived weights that make up the displacement are a function of only five variables; beam, draft, length at waterline, prismatic coefficient and the maximum transverse section coefficient. Working carefully through the model, calculations that were independent of the design variables are calculated in the math model and passed as-is to the optimizer, while those calculations that are dependent on the design variables are calculated in separate Matlab function M-files and all are brought together as the objective function to be optimized. The design

variables change names between the different applications so Table 1 provides a cross reference of the variable names to aid in navigating though the different applications.

Design Variable	Mathcad Variable Name	Matlab Variable Name
Beam	B	x(1)
Draft	T	x(2)
Length at Waterline	LWL	x(3)
Prismatic Coefficient	C_P	x(4)
Maximum Transverse Section Coefficient	C_X	x(5)

Table 1. Design Variable Description.

3. Constraints

The constraints that are incorporated into the optimizer are real, rational, engineering limitations on the design variables. They define what is a feasible design. The math model provides acceptable ranges for several coefficients and ratios and displays them in parentheses next to the current value on the summary page. These ranges are necessary to keep the designs within the valid range of the Taylor Standard Series [Ref. 12] for resistance calculations. The ranges are then converted to constraints for use in the optimizer. Inequality constraints include; Beam-to-Draft (C_{BT}), Length-to-Beam(C_{LB}), GM-to-Beam (C_{GMB}), and Displacement-to-Length ($C_{\Delta L}$). The acceptable ranges for the design variables C_P and C_X are included as side constraints in the "vlb, vub" command in Matlab. The side constraints for the remaining design variables are generated from design experience. Table 2 contains a summary of the constraints used in the optimizer. Note that Matlab requires the ranges to be split up and formatted as upper and lower inequality constraints.

Coefficient or Ratio	Range	Mathcad	Matlab Constraint Equation
Beam-to-Draft Ratio	2.8 - 3.7	C_{BT}	g(1)=(2.8*x(2)/x(1))-1 g(2)=(x(1)/(3.7*x(2)))-1
Length-to-Beam Ratio	7.5 - 10	C_{LB}	g(3)=((x(1)*7.5/x(3)))-1 g(4)=(x(3)/(x(1)*10))-1
GM-to-Beam Ratio	0.09 - 0.122	C_{GMB}	g(5)=(0.09*x(1)/GM)-1 g(6)=(GM/(0.122*x(1)))-1
Displacement-to-Length	45 - 65	$C_{\Delta L}$	g(7)=(45*((x(3)/100)^3/f)-1 g(8)=(f/(((x(3)/100)^3)*65))-1
Prismatic Coefficient	0.54 - 0.64	C_P	vlb = 0.54, vub = .064
Max Transverse Section	0.7 - 0.85	C_X	vlb = 0.7, vub = 0.85

Table 2. Constraint Summary.

IV. INTEGRATION AND LINKING OF COMPUTATIONAL SYSTEMS

A. MATHCONNEX PROGRAM DESCRIPTION

The MathConnex environment allows the user to integrate and link several types of application programs and data sources to form a single computational system. It uses a visual interface and it greatly simplifies the task of creating an integrated ship design synthesis program, which could otherwise be hobbled by the cumbersome data transfer requirements of the disparate computational elements.

MathConnex is capable of handling the three different applications used in the ship design program; Excel spreadsheets for the payload, Mathcad worksheets for the design synthesis, and the Matlab numerical optimizer. Each application is displayed as an icon on the worksheet with the associated data transfer "wires" connecting it to the other applications, see Figure 3. This plainly defines the program logic flow which follows the arrows on the wires. To view the contents of an application, one need only double click on the icon and the contents are displayed within the fully functional application window. When one is done with an application, clicking elsewhere on the worksheet collapses it back into an icon. This allows the inclusion of large application files and makes them easy to manipulate while keeping the overall program uncluttered on the MathConnex worksheet.

The data to be passed between applications is calculated and collected within each application for transfer to the next. It should be noted that each application is restricted to only four input and output ports, thus requiring most data to be gathered into arrays and assigned an appropriate transfer variable name, i.e. Input1, Ouput0, etc. Data transfer between the applications is handled by using click-and-drag wire connections between the

input/output ports on each icon. Once the data has been transferred, a similar variable transformation is accomplished to reassign the elements of the transfer arrays to the appropriate variable names in the next application.

At certain points during program processing it is desirable to view the intermediate results to ensure that the applications are generating useful data. The manner in which this is accomplished is the same as data transfer between applications, except the desired data is output to a view box on the worksheet.

MathConnex has enabled the integrated ship design system to fulfill the original intent of providing the student a design tool with a user friendly interface while greatly expanding the capabilities of the MIT Simplified Math Model through the addition of the numerical optimizer.

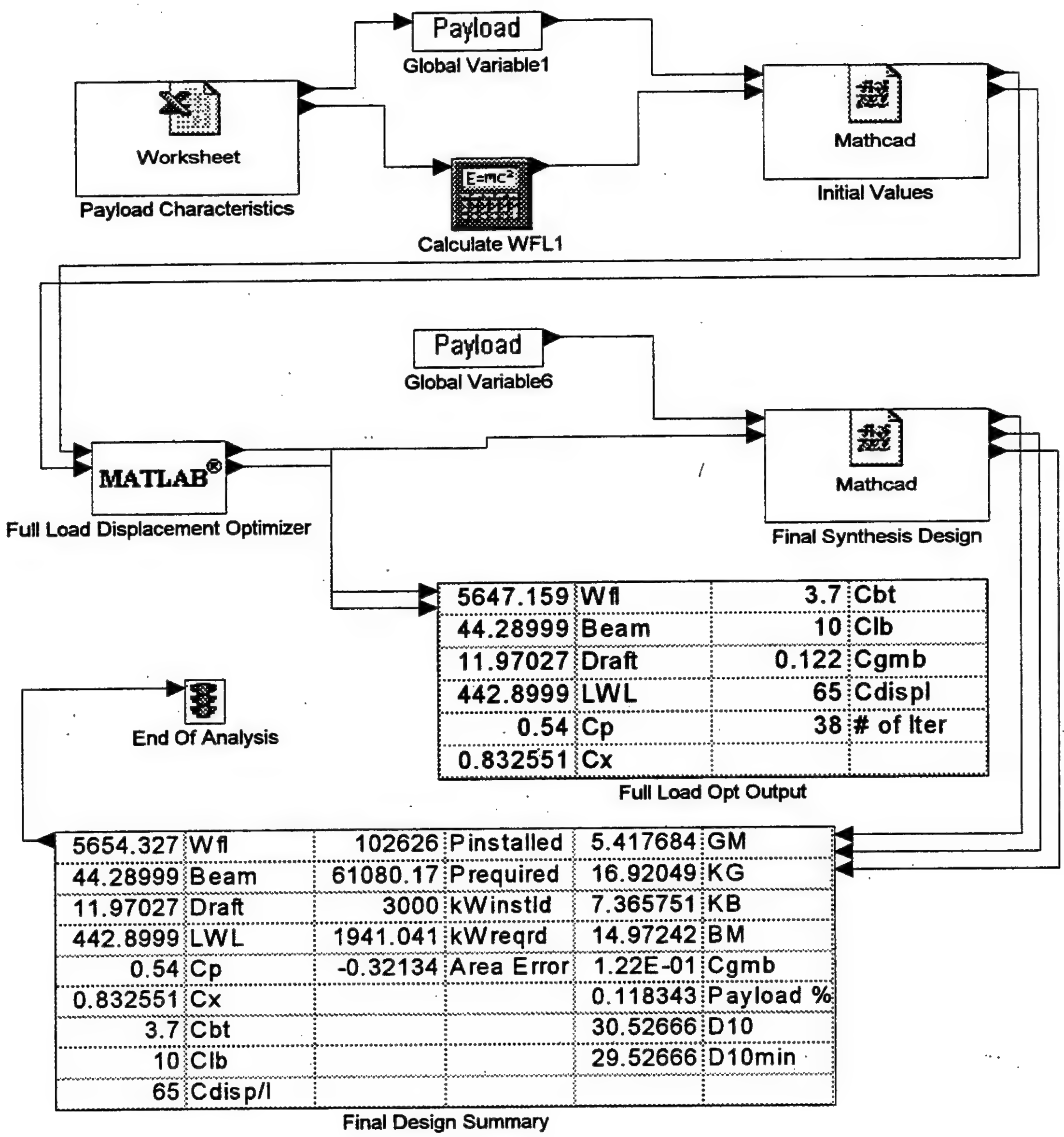


Figure 4. MathConnex Worksheet.

V. INTEGRATED SHIP DESIGN SYSTEM

A. PROGRAM DATA AND LOGIC FLOW

The previous section presented the general view of the operation and layout of the MathConnex worksheet. This section will present the detailed, step-by-step procedures that are executed in the Integrated Ship Design System (ISDS) worksheet as shown in Figure 4. Appendix G is a user's manual for the designer that provides the hands-on mechanics for proper set-up and use of the ISDS.

The ISDS MathConnex worksheet starts in the upper left hand corner with the Payload Characteristics contained in an Excel spreadsheet. By double-clicking on the icon, the Payload Characteristics spreadsheet is displayed on the screen. The designer then proceeds through the list of combat systems, modifying it to meet the specific payload for the desired design. The Excel spreadsheet then generates weight, area, stability and power data for the payload and transfers the array to Global Variable 1 and 6, "Payload", in the MathConnex worksheet. The total payload weight from the Excel spreadsheet is passed to the "Calculate WFL1" module to provide an initial guess of displacement.

The payload array and the displacement are then passed to the first Mathcad module, "Initial Values". This uses the math model to generate the initial values of the design variables and the non-design variable dependent weights and center of gravity information for use in the optimizer. Range, speed and manning data input by the designer are also passed to the optimizer and the "Final Synthesis Design" Mathcad module.

The Matlab module uses the transferred data to initialize the non-linear constrained optimizer to calculate the optimal minimal displacement and the associated design variable

values. This data, along with the constraint values and the number of optimizer iterations are output to the worksheet to provide intermediate evaluation of the design, and for later comparison to the final design synthesis results to check consistency. Additional detailed output from the optimizer can be viewed in a Matlab editor screen outside of the MathConnex environment. This data file, "outopt", contains important input data such as the initial guess for the design variables, and their side constraints. Output data includes updates of the objective function value for every six iterations, the magnitude of the constraint violation, and specifics regarding the algorithm search method. A message is also displayed which indicates if the optimization has successfully converged and identifies which constraints are active.

The optimal values of the design variables along with the original payload are transferred to the "Final Synthesis Design" Mathcad module. The math model calculates the final design and outputs selected design attributes to the screen. The complete design summary and all the calculations can be viewed by simply double-clicking on the "Final Synthesis Design" Mathcad module and scrolling through the pages. The stop light automatically toggles off the calculation.

B. DESIGN EXAMPLE

1. Payload Description

The effort required to define the payload and mission profile that the ship must fulfill is no trivial task. The guiding document, which is developed by the end user, is the Mission Needs Statement (MNS). This far-reaching document provides critical guidance, not only for the ship designer, but other acquisition programs, formulators of service and joint doctrines and cooperative efforts with our allies. The MNS that is utilized in this design example provides the requirements for expeditionary force surface combatants for the 21st century (i.e. SC-21) as modified at MIT for use in the Principles of Naval Ship Design (Course 13.412) when it was offered in the fall of 1997. The MNS lays the foundation for the DD-13A Background and Requirements Document, which provides a summary of combat systems that are arrayed into three variants to meet escalating needs.

This design example uses the DD-13A Medium Variant (Payload #2) with the following additional modifications;

⇒ Manning: 15 Officers, 135 Enlisted

⇒ Average Deck Height: 9 feet

⇒ Sustained Speed: 27 knots

⇒ Endurance: 7500 nautical miles

⇒ Stores Period: 45 days

⇒ Fin Stabilizers: None

⇒ CPS System: Full

⇒ Propulsion: Mechanical Drive LM-2500, 2 per shaft, 2 shafts, no APU's

⇒ Ship's Service Power: DDA 501-K34

The MNS, the DD-13A Background and Requirements Document, and the payload spreadsheet are contained in Appendix B.

2. Optimized Design Results

Before the initial run through the optimizer, the designer must assign values to the side constraints for the first three design variables in the Matlab module on the MathConnex worksheet. An upper and lower value for the beam, waterline length and draft will come from experience, but can be guided by real world constraints such as limiting the maximum beam to allow passage through the Panama Canal, or restricting maximum draft to allow transit to different ports around the world. The setting of these side constraints limits the design space to be searched by the optimizer, and creates the possibility that a local, vice global minimum may be returned if the side constraints are too limiting. Expanding and contracting the side constraints to investigate the full design space should be attempted for every design considered. The side constraints for C_P and C_X are fixed by the acceptable ranges permitted in the math model.

The optimizer should be sufficiently robust that any initial guess of the design variables returns the same optimum value of the objective function and design variables. The ISDS uses the data generated by the "Initial Values" Mathcad module for the first guess of the design variables ("x0") in the optimizer. This first guess can be easily changed by toggling on the designer-provided guess line in the Matlab module.

The optimizer will return a solution to the MathConnex worksheet even if the constraints force an infeasible solution, though the Matlab command window output data file will print a warning that no feasible solution has been found. The designer must

remain keenly aware when reviewing solutions in MathConnex to cross check the command window to ensure the optimizer has returned a feasible solution that has converged.

Six different runs with the ISDS were completed using the previously described payload to capture all the above possibilities. Detailed results of the Mathcad math model and optimizer outputs are in Appendix E, the combined results are in Table 3.

Design Attribute	Initial Run			Expand Side Constraints			High Value Initial Guess		
	Results	vlb-vub	x0	Results	vlb-vub	x0	Results	vlb-vub	x0
Displacement, Wfl (lton)	6123.424			6123.424			6123.424		
Beam, B (ft)	45.50163	40 to 70	55.745	45.50163	20 to 90	55.745	45.50163	20 to 90	100
Draft, T (ft)	12.29774	10 to 30	16.892	12.29774	5 to 40	16.892	12.29774	5 to 40	100
Waterline Length, LWL (ft)	455.0163	400 to 700	495.3	455.0163	200 to 800	495.3	455.0163	200 to 800	1000
Prismatic Coefficient, Cp	0.54	.54 to .64	0.6	0.54	.54 to .64	0.6	0.54	.54 to .64	10
Max Transverse Section, Cx	0.787983	.70 to .85	0.75	0.787983	.70 to .85	0.75	0.787983	.70 to .85	10
Beam-to-Draft, Cbt	3.7			3.7			3.7		
Length-to-Beam, Clb	10			10			10		
GM-to-Beam, Cgmb	0.122			0.122			0.122		
Displacement-to-Length, Cdl	65			65			65		
Number of Iterations	31			31			109		

Design Attribute	Low Value Initial Guess			Constrainted Above Optimum			Constrained Below Optimum		
	Results	vlb-vub	x0	Results	vlb-vub	x0	Results	vlb-vub	x0
Displacement, Wfl (lton)	6123.424			7182.628			4729.255		
Beam, B (ft)	45.50163	40 to 70	0	50	50 to 90	55.745	40.22113	20 to 90	55.745
Draft, T (ft)	12.29774	10 to 30	0	15	15 to 40	16.892	10.41899	5 to 10	16.892
Waterline Length, LWL (ft)	455.0163	400 to 700	0	500	500 to 800	495.3	406.4662	200 to 800	495.3
Prismatic Coefficient, Cp	0.54	.54 to .64	0	0.54	.54 to .64	0.6	0.121007	.54 to .64	0.6
Max Transverse Section, Cx	0.787983	.70 to .85	0	0.770449	.70 to .85	0.75	0.281007	.70 to .85	0.75
Beam-to-Draft, Cbt	3.7			3.333333			3.860366		
Length-to-Beam, Clb	10			10			10.10579	Warning: No feasible solution found.	
GM-to-Beam, Cgmb.	0.122			0.122			-0.33549		
Displacement-to-Length, Cdl	65			57.46102			70.42378		
Number of Iterations	49			32			37		

Table 3. Results from Optimizer Using Constant Payload.

The initial run used the output values from the "Initial Value" Mathcad model to provide the first guess of the design variables. The side constraints were set assuming a sufficient range to cover the expected size of the ship. The optimization converged successfully with four constraints remaining active (g(2), g(4), g(6), g(8)). To ensure that this was not a local minimum, the next run increased the range of the side constraints to cover more of the design space, while keeping the initial guess constant. The results were exactly the same, so this does appear to be a global minimum.

To check the performance capabilities of the optimizer, unrealistically high values for the initial guess were used, while the side constraints remained constant. The optimizer performed very well; it found the same optimum, but it took almost four times the number of iterations to converge on the solution. Correspondingly, the initial guess was set at zero to see if it would find the same optimum from below, which it did using only half the number of iterations required for the high initial guess.

As a final check of the capabilities of the optimizer, the side constraints were changed to exclude the location of the global minimum in the design space. When the lower side constraints were moved above the global minimum, a new local minimum was found that was equal to the new lower side constraints. This is an expected and feasible result, and one which should alert the designer to expand the design space and continue to search for the global optimum. Finally, the upper side constraint for draft was set lower than the optimal value. This resulted in no feasible solution being found, and the optimizer discontinued the search and printed the appropriate warning message. Note that the optimizer did output results, but that most of the constraints are quite obviously violated

and this should alert the designer to double check the Matlab command window data file output for warning messages.

The previous effort has definitively located the global minimal displacement for the given payload and constraints using the Matlab optimizer. A few additional checks must be made to ensure that the final design is feasible within the constraints of the math model. The final design summary in MathConnex contains data that needs to be compared to ensure the design is feasible; these include the installed versus required propulsion power and ship service electrical power and area and weight errors. If any of these are outside the designer-defined limits, adjustments to the characteristic inputs in the payload and math model must be made and the optimization process started again.

3. Comparison of Optimized versus Non-Optimized Design Results

The previous section demonstrates the ability of the ISDS to successfully link the Matlab optimizer with the MIT Math Model and produce a feasible design. The ISDS also behaved predictably when tested with unrealistic constraints and initial design variable guesses. The next logical question is does the ISDS produce a ship design of less displacement than if one used the MIT Math Model alone?

When using the MIT Math Model without the optimizer, several of the coefficient values are held fixed. The values assigned to these coefficients are chosen at the middle of the acceptable range to reduce any bias for this example;

$$C_P = .59,\ C_X = .775,\ C_{BT} = 3.25,\ C_{\Delta L} = 55.$$

Six iterations were required to bring the weight error below one percent and Table 4 shows the results of the optimized versus non-optimized design.

The non-optimized design is nearly feasible with the exception that C_{GMB} is outside of the acceptable range, the ship's service power requirement is slightly high and the area requirement is overstated by 20 percent. Though it is nearly feasible, it is not optimal, there is a 36 percent difference in displacement, a 26 percent reduction in payload fraction and almost an eight and one half percent increase in cost. The greatest difference between the optimized and non-optimized models is in the value of GM, a 127 percent difference. GM is defined as;

$$GM := KB + BM - KG$$

A closer look reveals that KG has a minimal difference between the two methods, the biggest changes are in KB and BM. BM is a cubic function in beam;

$$BM := \frac{LWL \cdot B^3 \cdot C_{IT}}{12 \cdot V_{FL}}$$

so small changes in beam result in large changes in BM. Beam is a function of displacement and the variable form coefficients C_P, C_X, and C_{BT};

$$B \equiv \sqrt{\frac{C_{BT} \cdot V_{FL}}{C_P \cdot C_X \cdot LWL}}$$

and by fixing the values of the form coefficients in the middle of the range the, beam is forced to remain fairly large.

To demonstrates the sensitivity of B, BM, and GM, the starting displacement is held constant from before and moderate changes to the values of the form coefficients (±10%) are made and the results tabulated in Table 5. The results show that changes to the form coefficients are almost one-for-one to changes in the beam (-15%), while draft and length remain essentially constant. The greatest difference though is in stability; GM

and BM drop dramatically, 55% and 31% respectively and these changes produce a feasible design, with the exception of area which can be adjusted for with minimal overall impact to the rest of the design.

This clearly demonstrates the influence of the coefficients of form in the math model, and how advantageous it is to have an ability to easily manipulate them during the design process. The ISDS provides this capability through its use of the optimizer which enables the entire design space to be considered simultaneously, instead of one small piece when the MIT Math Model is used alone.

Non-Optimized	Design Attribute	Non-Optimized	Percent Difference
8359.500026	Wfl (lton)	7879.850351	-5.73777946
62.24414674	Beam (ft)	53.12115024	-14.65679422
19.15204515	Draft (ft)	18.97183937	-0.940921866
532.1307151	LWL (ft)	533.66969	0.289209927
0.59	Cp	0.64	8.474576271
0.775	Cx	0.85	9.677419355
3.25	Cbt	2.8	-13.84615385
8.549088436	Clb	10.04627512	17.51282251
55 (fixed)	Cdisp/l	55 (fixed)	
102626	Pinstalled (hp)	102626	
85806.67845	Prequired (hp)	85232.82952	-0.668769539
3000	kWinstld (kW)	3000	
3023.538718	kWreqrd(kw)	2745.998472	-9.179318373
0.204919419	Area Error	0.264553987	
-0.008626356	Weight Error	0.060870401	
12.68761149	GM (ft)	5.654802214	-55.43052198
19.66127644	KG (ft)	19.66713065	0.029775361
11.95711557	KB (ft)	11.34806536	-5.093621459
20.39177236	BM (ft)	13.9738675	-31.47301148
2.04E-01	Cgmb	1.06E-01	-47.77618486
8.064060715	Payload %	7.994497279	-0.862635325
1103.21963	Cost, $Mil	1087.107089	-1.46050164
6	# of Iterations	1	

Table 5. Comparison of Modified Coefficients of Form in MIT Math Model.
(Note, shaded results violate model constraints.)

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The goal of this research effort was to improve the functionality the MIT Simplified Math Model by adding a numerical optimization capability that would deliver optimal and reasonable ship designs. This goal has been met, and even exceeded in some respects. MathConnex enables the ISDS to use all three application programs simultaneously in a singular, user friendly environment and presents consolidated results that can be easily checked for reasonableness and accuracy. This aids the designer in the ability to investigate more designs in the same amount of time than when using the MIT Math Model alone.

The ISDS and the MIT Math Model both produce feasible and reasonable designs, though they solve the problem in a fundamentally different way. The MIT Math Model takes a displacement and calculates the gross characteristics of beam, draft and length for a given set of fixed coefficients of form. The ISDS, though using the same mathematical basis for calculation, uses the gross characteristics and variable, but constrained, coefficients of form to calculate the displacement. This makes the ISDS a more flexible design tool through its ability to consider the entire design space during the feasibility study.

It is the Matlab optimizer that permits ISDS this flexibility. Its ability to take a multivariable, constrained design problem and return an optimum displacement value using fairly simple user supplied algorithms is key to the system's success. It is the positive synergistic effects of mating the math model with the optimizer that makes this such a powerful design tool.

B. RECOMMENDATIONS

This study was limited to investigating only one objective function, displacement. Efforts were focused on successfully integrating the different applications in the MathConnex environment and translating the Mathcad algorithms into Matlab function M-files in the optimizer. Fine tuning the optimizer to return consistent results with the MIT Math Model also required significant effort. The function M-files in the optimizer should lend themselves to easy manipulation for follow-on studies to develop different objective functions for optimization. A particularly relevant objective function in the current fiscal environment would be cost minimization. Another interesting area would be investigating the feasibility of power limited designs and comparing them to the current practice payload limited designs.

In conclusion, the ISDS is a design tool that possesses numerous characteristics that make it very attractive to the student and designer. As with any software program, understanding how the elements operate and interact is crucial to ensuring valid results. Gaining a thorough working knowledge of the MIT Math Model and ISDS User's Guide in Appendix G is the best way to guarantee that the optimum design is returned.

APPENDIX A. GLOSSARY

Coefficients of Form: Geometric qualities of the ship that can be related as ratios or dimensionless coefficients. Useful in comparing certain performance characteristics associated with hydrodynamic phenomena.

Prismatic Coefficient (C_P): The ratio of the volume of displacement (∇ or V_{FL}) to the volume of a prism having waterline length (LWL) and a cross section equal in area to that of the maximum section at the designated waterline.

Maximum Transverse Section Coefficient (C_X): The ratio of the maximum transverse section area to the product of the beam (B) and draft (T) at this section.

Beam-to-Draft Ratio (C_{BT}): Ratio of the beam (B) to the draft (T).

Displacement-to-Length Ratio ($C_{\Delta L}$): The ratio of the full load displacement, in long tons, (Δ_{FL} or W_{FL}) to the waterline length (LWL) in feet.

$$C_{\Delta L} := \frac{\Delta_{FL}}{\left(\frac{LWL}{100}\right)^3}$$

Length-to-Beam Ratio (C_{LB}): Ratio of the waterline length (LWL) to the beam (B).

Sheer Line: The line of intersection of the main or weather deck with the side of the ship.

Objective Function: The relationship that expresses the interdependence of the design variables and is the function to be optimized.

Constraint Function: Explicit or implicit functions of the design variables that limit the design space that is searched to ensure feasibility of the solution.

Active Constraint: An active constraint is one where the optimal solution lies on the constraint boundary.

Function M-file: Matlab file that allows the designer to create new mathematical functions that are added to the existing library of Matlab functions. A function M-file passes arguments in and out of its local workspace to reduce clutter in the main working environment.

GM: The distance between the ship's vertical center of gravity and its metacenter.

KB: The distance between the ship's baseline or keel and the vertical center of buoyancy.

BM: The distance between the ship's vertical center of buoyancy and its metacenter.

KB: The distance between the ship's baseline or keel and the vertical center of buoyancy.

Transverse Waterplane Inertia Coefficient (C_{IT}): The ratio of the moment of inertia of the waterplane area to that of the circumscribing rectangle in the transverse direction.

Underwater Volume (V_{FL}): The volume of water displaced at full load.

APPENDIX B. MIT SIMPLIFIED MATH MODEL PAYLOAD SPREADSHEET

DD13A
PAYLOAD

PAYLOAD NAME	*WT KEY*	*WT*	*VCG DATUM*	*VCG FT AD*	*AREA KEY*	*HULL FT2*	*DKHS FT2*	*CRUISE KW*	*BATTLE KW*
STEEL LANDING PAD [ON HULL] - SH-60 CAPABLE	W111	10.7	36.717	0.20	NONE	0	0	0	0
128 CELL VLS ARMOR - LEVEL III HY-80	W164	56	38.31575	-10	NONE	0	0	0	0
VGAS HY-80 ARMOR LEVEL II	W164	3	33.4	18.3	NONE	0	0	0	0
SQS-53C 5M BOW SONAR DOME	W165	85.7	0	-1.5	NONE	0	0	0	0
GROUP 100	**WP100**	155.4				0	0	0	0
CIC W/UYQ-44 & 2X LSD	W410	19.34	0	35.58	A1131	1953	448	45.03	45.03
NAVIGATION SYSTEM	W420	7.29	51	14.00	A1132	0	848.3	55.99	53.5
ADVANCED DIGITAL C4I (JTIDS/LINK 16/LINK22/TADIXS/TACINTEL)	W440	37.91	51	-46.84	A1110	1230.6	1270.4	35.76	39.67
SPS-67 SURFACE SEARCH RADAR	W451	1.81	51	-10.00	A1121	0	70	8	0
ADVANCED IFF	W455	2.32	51	-5.00	NONE	0	0	3.2	4
SPY-1D MFAR -- SINGLE TRANSMITTER	W456	58.67	33.4	15.84	A1121	0	1828	291.4	345.18
X-BAND RADAR AND FOUNDATION, 110 FT ABOVE BL	W456	4.11	0	113.00	NONE	0	0	220.16	220.16
SQS-53C 5M BOW SONAR DOME ELEX	W463	57.7	0	9.3	A1122	1942	0	39	39
LIGHTWEIGHT BROADBAND VARIABLE DEPTH SONAR (LBVDS)	W464	0.24	36.717	-6.20	A1142	200	0	3	4.2
SSQ-61 BATHYTHERMOGRAPH	W465	0.31	36.717	-10.90	A1122	85.5	0	0	0
SQQ-28 SONOBUOY PROCESSING SYSTEM	W466	5.26	51	-44.86	NONE	0	0	1.15	1.15
ADVANCED INTEGRATED ELECTRONIC WARFARE SYSTEM (AIEWS)	W472	4.4	33.4	20.60	NONE	0	0	6.4	6.4
AN/SLQ-25A NIXIE	W473	0.24	36.717	-6.20	A1142	200	0	3	4.2
MK36 DLS W/6 LAUNCHERS	W474	0.96	33.4	5.39	NONE	0	0	2.4	2.4
MINEHUNTING AUV / REMOTE MINEHUNTING SYSTEM	W478	0.24	36.717	-6.20	A1142	200	0	3	4.2
AEGIS-BASED VGAS GFCS [UYQ-21 + UYK-44]	W481	3.32	33.4	0.00	NONE	0	0	9.84	11.77
AN/SWG-1 HARPOON CONTROL IN CIC	W482	1.14	38.31575	10.80	NONE	0	0	0	4.9
MK99 GMFCS W/CEC W/3 SPG-62 ILLUM	W482	14.29	33.4	20.90	A1220	0	959	13.4	30.88
VLS WEAPON CONTROL SYSTEM	W482	0.7	38.31575	-7.80	A1220	56	310	13.62	19.69
ADVANCED TACTICAL WEAPON CONTROL SYSTEM (ATWCS)	W482	5.6	33.4	-7.80	NONE	0	0	13.27	13.27
ASW CONTROL SYSTEM w/SSTD [ASWCS]	W483	3.75	33.4	-12.60	A1240	320	0	8.61	8.61
COMBAT DF	W495	8.26	33.4	21.00	A1141	0	448	15.47	19.34
ELECTRONIC TEST & CHECKOUT	W499	1.1	38.31575	10.80	NONE	0	0	0	0
GROUP 400	**WP400**	238.96				6187.1	6181.7	791.7	877.55
FWD 64-CELL VLS MAGAZINE DEWATERING SYSTEM	W529	7	35.0585	-0.46	NONE	0	0	0	0
AFT 64-CELL VLS MAGAZINE DEWATERING SYSTEM	W529	7	35.0585	-0.46	NONE	0	0	0	0
COOLING EQUIPMENT FOR SPY-1D	W532	9	33.4	-34.00	A1121	0	960.8	0	0
COOLING ADJUSTMENT FOR X-BAND RADAR	W532	4.43	0	9.81	A1121	47.85	0	13.64	13.64
LAMPS MKIII AVIATION FUEL SYS	W542	4.86	35.0585	-11.00	A1380	30	0	2	2.9
LAMPS MKIII RAST/RAST CONTROL/HELO CONTROL	W588	31.1	35.0585	-1.60	A1312	219	33	4.4	4.4
GROUP 500	**WP500**	63.39				296.85	993.8	20.04	20.94
SQS-53C 5M BOW SONAR DOME HULL DAMPING	W636	6.7	0	-2.5	NONE	0	0	0	0
LAMPS MKIII AVIATION SHOP AND OFFICE	W665	1.04	35.0585	-4.50	A1360	194	75	0	0
GROUP 600	**WP600**	7.74				194	75	0	0
VGAS 155 MM	W710	10.2	33.4	18.30	A1214	0	533	10	34
2X HARPOON SSM QUAD CANNISTER LAUNCHERS	W721	4.1	33.4	1.17	A1220	0	0	0	1.6
FWD MK41 VLS 64-CELL	W721	107.72	35.0585	1.14	A1220	128	0	69.65	69.65
AFT MK41 VLS 64-CELL	W721	107.72	35.0585	1.14	A1220	128	0	69.65	69.65
2X MK32 SVTT ON DECK	W750	5.55	33.4	2.20	A1244	0	368	2	5
GROUP 700	**W7**	235.29				256	901	151.3	179.9
VGAS AMMO -- 680 RDS	WF21	11.3	33.4	13.60	NONE	0	0	0	0
HARPOON MISSILES -- 8 RDS IN CANNISTERS	WF21	3.78	33.4	5.00	NONE	0	0	0	0
AFT MK 41 LAUNCHER MISSILE LOADOUT (ESSM, SM. VLA, TLAM, ATACMS)	WF21	144	35.0585	0.34	A1220	1420	720	0	0
FWD MK 41 LAUNCHER MISSILE LOADOUT (ESSM, SM, VLA, TLAM, ATACMS)	WF21	144	35.0585	0.34	A1220	1420	720	0	0
MK46 LWT ASW TORPEDOES -- 6 RDS IN SVTT TUBES	WF21	1.36	33.4	2.50	A1240	368	0	0	0
MK36 DLS SRBOC CANNISTERS - 100 RDS	WF21	2.2	33.4	11.60	NONE	0	0	0	0
SMALL ARMS AMMO - 7.62MM + 50 CAL + PYRO	WF21	4.1	33.4	-6	NONE	0	0	0	0
LAMPS MKIII 18 X MK46 TORP & SONOBUOYS & PYRO	WF22	9.87	35.0585	4.80	A1374	0	588	0	0
LAMPS MKIII 2 X SH-60B HELOS, UAV'S, AND HANGAR (BASED)	WF23	12.73	35.0585	4.50	A1340	0	3406	5.6	5.6
LAMPS MKIII AVIATION SUPPORT AND SPARES	WF26	9.42	35.0585	5.00	A1390	357	0	0	0
BATHYTHERMOGRAPH PROBES	WF29	0.21	36.717	-6.00	NONE	0	0	0	0
GROUP WF20	**WF20**	342.97				3565	5434	5.6	5.6
LAMPS MKIII:AVIATION FUEL [JP-5]	**WF42**	63.8	0	10.4	A1380	0	0	0	0
VARIABLE MILITARY PAYLOAD (WF20+WF42)	**WVP**	406.77							
ARMAMENT (WP500,WP600,W7,WF20)						4311.85	7403.8		
								KWP	
TOTAL PAYLOAD	***WP***	1107.6				10499	13585.5	968.64	1083.99
DATUM DEFINITIONS:									
	DEPTH0	47.445		VCG P:	0.00				
	DEPTH3	43.232		VCG VP:	0.00				
	DEPTH6.5	38.316							
	DEPTH10	33.4							
	DEPTH15	35.059							
	DEPTH20	36.717							
	BL	0							
	MAST BAS	51							

APPENDIX C. MIT SIMPLIFIED MATH MODEL MATHCAD WORKSHEET SUPPORTING DOCUMENTATION

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Department of Ocean Engineering

13.412 Handout

SIMPLIFIED MATH MODEL FOR THE DESIGN OF NAVAL FRIGATES

Adapted from the US Navy Synthesis Model by
C. Graham
R. Hamly
September, 1975

Revised by
C. Graham and J. Reed: September, 1986

D. Peer: 16 July 1990

C.B. Sweeney: August, 1991

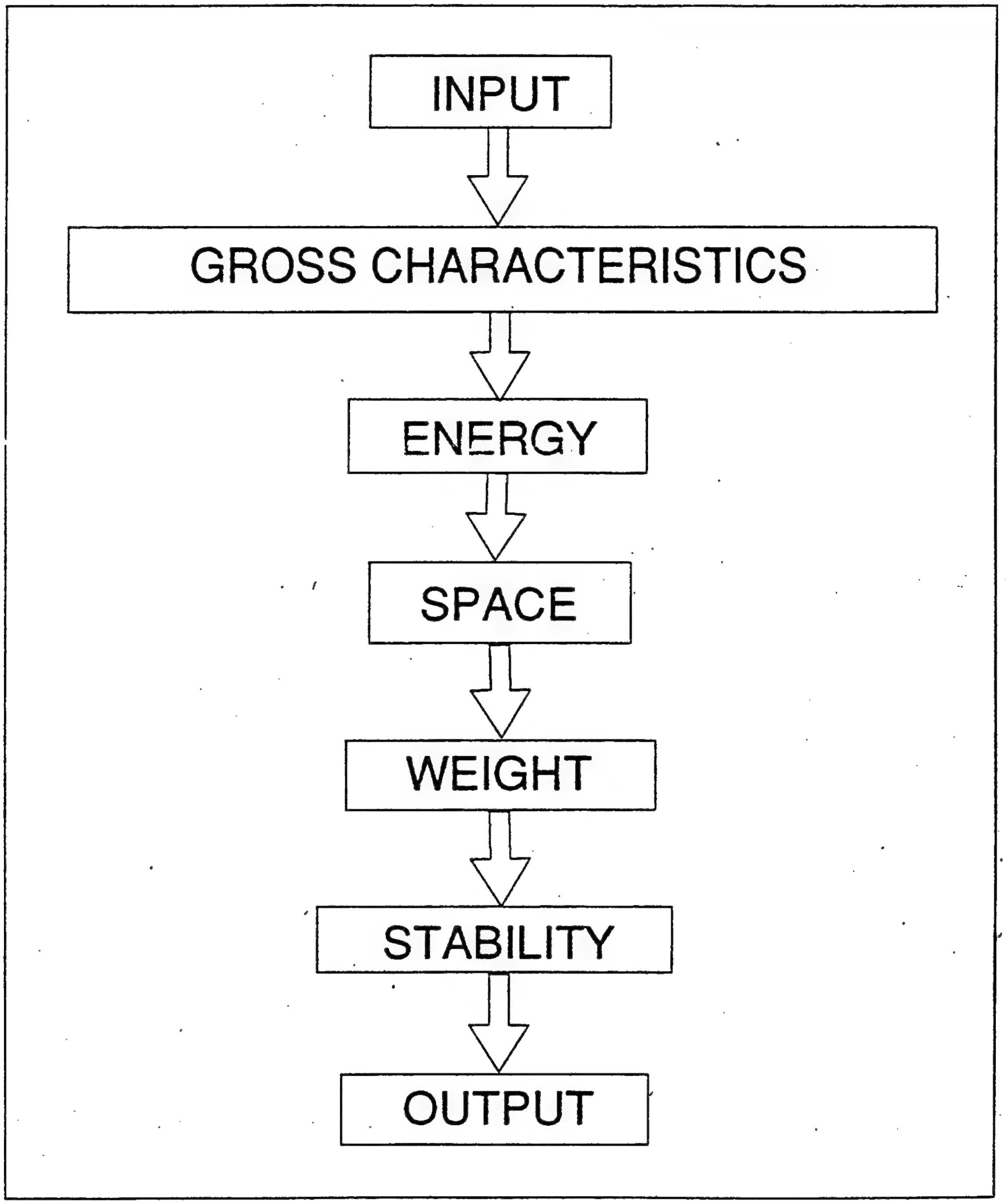
LIST OF REVISIONS

Rev	Author	Date	Description
1	G. Hottel K. McCoy	24 Dec 88	General Revision
2	D.Peer	4 Jun 90	-Added table of Revision -Changed L/D limit to 15 -Corrected hull vol avail to account for volume of auxiliaries -Moved donar dome water from load weights to weight group 4 -Changed bearing weight to account for propeller weight
3	C.B Sweeney	1 Aug 91	Clarifications added, general revision and conversion to Word Perfect 5.1 files

__List of Enclosures__

Enclosure (1): Math Model Macro Flow Diagram
Enclosure (2): Symbols Used in Math Model
Enclosure (3): Micro Flow Diagrams for Frigate Math Model
Enclosure (4): Taylor Standard Series Made Easy
Enclosure (5): Energy Balance Module

MATH MODEL MACRO FLOW DIAGRAM



SYMBOLS USED IN MATH MODEL

I. INPUT SYMBOLS

A_{DPA}	Payload deck area in deckhouse - armament, ft^2
A_{DPC}	Payload deck area in deckhouse - command/control, ft^2
A_{HPA}	Payload deck area in hull - armament, ft^2
A_{HPC}	Payload deck area in hull - command/control, ft^2
B_{MB}	Width of machinery box, ft
C_A	Correlation coefficient = 0.0005
E	Endurance range at Ve , nautical miles
EP_{CHL}	Endurance period chilled provisions, days
EP_{DRY}	Endurance period dry goods, days
EP_{FRZ}	Endurance period frozen provisions, days
EP_{GSM}	Endurance period general stores, days
FR	Propulsion fuel rate at V_e, lbs/SHP-hr
FR_G	Generator fuel rate, lbs/kW-hr
H_T	Height between decks, ft
H_{MB}	Height of machinery box, ft
kW_B	Battle electrical load, kW
kW_{24}	Average 24 hour electrical load, kW
L_{MB}	Length of machinery box, ft
N_E	Number of enlisted accommodations
N_O	Number of officer accommodations
N_S	Number of shafts
N_T	Total number of accommodations
PC	Propulsive coefficient
P_I	Installed shaft horsepower
V_e	Endurance speed, knots
V_s	Maximum sustained speed, knots
W_A	Ammo weight, tons
W_H	Helo weight, tons
W_{HF}	Weight of helo fuel, tons
W_{LO}	Weight of lube oil, tons

W_{MT}	Weight of masts, tons
W_P	Payload weight
W_{PA}	Payload weight - armament, tons
W_{PC}	Payload weight - command and control, tons
W_{SD}	Weight of sonar dome, tons
W_{SW}	Weight of sea water in sonar dome, tons
γ	Specific volumes, ft^3/ton
∇_{VOID}	Tankage volume, voids, ft^3

II. GROSS CHARACTERISTICS SYMBOLS

A_m	Area of maximum section, ft^2
B	Ship beam, ft
C_M	Midship section coefficient, $C_M = C_X$
C_P	Prismatic coefficient, $\nabla_{HV}/(A_X \bullet L)$
C_V	Volumetric coefficient
C_X	Maximum section coefficient, $A_M/(B \bullet T)$
L	Ship length, ft
T	Ship draft, ft
$V/L^{.5}$	Speed to length ratio, knot $/\sqrt{ft}$
Δ_{FL}	Full load displacement, tons
Δ_L	Displacement to length ratio, ton/ft^3
Δ_{HV}	Underwater hull volume, ft^3

III. ENERGY SYMBOLS

D_P	Propeller diameter, ft
P_S	Effective horsepower = PC*SHP = $V*R_T/325.6$
EHP_{BH}	Bare hull effective horsepower
EHP_{BHT}	Bare hull effective horsepower predicted by Taylor Series
P_e	Propulsive power at Ve, shaft horsepower
P_I	Installed power, shaft horsepower
P_{Ir}	Shaft horsepower required to be installed to meet demand
P_s	Propulsive power at V_s, shaft horsepower
R_T	Total ship resistance, lbs
W_F	Endurance fuel weight, tons

IV. SPACE SYMBOLS

A_{DA}	Deck area available in deckhouse, ft^2
A_{DB}	Deck area in deck house for bridge and chartroom, ft^2
A_{DL}	Deck area in deck house for living, ft^2
A_{DM}	Deck area in deck house for maintenance and access, ft^2
A_{DPR}	Total payload deck area required in deck house, ft^2
A_{DR}	Total arrangement deck area required in deck house, ft^2
A_{DSF}	Deck area in deck house for "ship" functions, ft^2
A_{HA}	Deck area available in hull, ft^2
A_{HAB}	Habitability allowance, ft^2/man
A_{HL}	Deck area in hull for living, ft^2
A_{HPR}	Total payload deck area required in hull, ft^2
A_{HR}	Total arrangement deck area required in hull, ft^2
A_{HS}	Stores deck area in hull, ft^2
A_{HSF}	Deck area in hull for "ship" functions, ft^2
A_{MB}	Cross sectional area of machinery box, ft^2
A_{PRO}	Projected area of hull above water, ft^2
CN	Cubic number = $L * B * D_{AV} * 10^{-5}$, ft^3
C_{PMB}	Prismatic coefficient of machinery box $=V_{MB}/(L_{MB}*A_{MB})$
D_{AV}	Average hull depth, ft
D_{MB}	Hull depth in vicinity of machinery box, ft
D_0	Depth at station 0, ft
D_{10}	Depth at station 10, ft
D_{10R}	Depth at station 10; roll criteria, ft
D_{10MB}	Depth at station 10; machinery box criteria, ft
D_{10BC}	Depth at station 10; bending moment criteria, ft
D20	Depth at station 20, ft
faux	Auxiliary space factor; class dependent
f_f	Flare factor
F_{AV}	Average freeboard, ft
F_0	Freeboard at station 0, ft
F_{10}	Freeboard at station 10, ft
F_{20}	Freeboard at station 20, ft

H_A	Helo deck area in the hangar, ft^2
I_{VD}	Intake volume, deckhouse, ft^3
I_{VH}	Intake volume, hull, ft^3
K_1	Allowance factor for structure
K_2	Allowance factor for expansion
W_W	Weight of potable water, tons
V_{aux}	Volume of auxiliary spaces, ft^3
V_D	Deck house volume, ft^3
V_{DR}	Total arrangement volume required in deck house, ft^3
V_{HA}	Hull arrangement volume available, ft^3
V_{HAW}	Hull volume above water, ft^3
V_{HR}	Total arrangement volume required in hull, ft^3
V_{HT}	Total hull volume available, ft^3
V_{MB}	Volume of machinery box, ft^3
V_T	Total ship volume available, ft^3
V_{TA}	Total arrangement volume available, ft^3
V_{TK}	Tankage volume, ft^3
V_{TR}	Total arrangement volume required, ft^3

V. WEIGHT SYMBOLS (All weights in long tons, 2240 lbs)

f_m	Deck house material factor
kW_I	Installed electrical capacity, kW
W_B	Shaft bearing weight
W_{BA}	Weight of basic auxiliary systems
W_{BH}	Weight of basic hull
W_{BM}	Weight of basic machinery
W_C	Weight of crew
W_{CC}	Weight of cable for command and control equipment
W_{CG}	Weight of gyro and interior communications equipment
W_{CO}	Weight of other command and control equipment
W_{DH}	Weight of deck house
W_{FD}	Weight of foundations

W_g	Weight margin
W_{GSM}	Weight of general stores
W_L	Light ship weight
W_{LD}	Weight of load items
W_{margin}	Weight margin factor
W_{OFH}	Weight of hull related outfit and furnishings
W_{OFP}	Weight of personnel related outfit and furnishings
W_{PR}	Propeller weight
W_{PRV}	Weight of provisions
W_s	Shafting weight per unit length, tons/ft
W_S	Shafting weight
W_{SS}	Weight of auxiliary steam system
W_{ST}	Weight of total shaft system
W_{SW}	Weight of seawater in sonar dome
W_T	Total weight
W_W	Weight of potable water
W_1	Hull structure weight
W_2	Propulsion machinery weight
W_3	Electrical plant weight
W_4	Communications and control weight
W_5	Auxiliary systems weight
W_6	Outfit and furnishings weight
W_7	Armament weight

VI. STABILITY SYMBOLS

A_W	Area of waterplane, ft^2
BM	Metacentric radius, ft
C_{IT}	Transverse (area) inertia coefficient= $I_W/(L*B^3)$
C_W	Waterplane area coefficient = $A_W/(B*L)$
GM	Ship transverse metacentric height, ft
I_W	Transverse area moment of inertia of the waterplane= $BM*\nabla_{HV}$
KB	Ship vertical center of buoyancy, ft

KG	Ship vertical center of gravity, ft
KG_L	KG of Light Ship with KG margin
KG_{LD}	KG of loads
KG_{Lsm}	KG of Light Ship without KG margin
KG_{margin}	Margin on light ship KG
M_{LD}	Moment of loads relative to base line, ft-tons (use subscripts corresponding to individual load item)
M_T	Total moment of all weight groups (includes margins), ft-tons
M_{WG}	Moment of weight group relative to baseline, ft-tons (use subscripts corresponding to individual weight group)
VCG_{WG}	Vertical Center of gravity of weight group above baseline, ft (use subscripts corresponding to individual weight group)

MICRO FLOW DIAGRAMS FOR FRIGATE MATH MODEL

I. INPUT

Input: Owner - Performance Requirements, Constraints, and Design Philosophy expressed in Top Level Requirements

Designer - Component/Subsystem Selection, Design Standards and Practices, Specific Design Parameters and Design Philosophy

TLR (Owner)
Design Philosophy

I1. **"Design to" Requirements (Goals, Thresholds)**
"Design to" Constraints"

↓

I2. Component/Subsystems
Design Philosophy

↓

Adjustment to Model

↓

I3. Design Practices and Standards
Design Philosophy

↓

Adjustment to Model

↓

I4. Specific Design Parameters
Design Philosophy

↓

Adjustment to Model

↓

Useful Output : Input file for specific ships

II. GROSS CHARACTERISTICS

Input: W_P, V_S

$$W_P = W_{PA} + W_{PC} + W_A + W_H + W_{HF}$$

II1. W_P/Δ_{FL}

(Figure 1)

↓

Δ_{FL}

↓

II2. V_S

Δ_L

↓

L

↓

II3. $C_P = f(V_S/\sqrt{L})$

$C_X = f(V_S/\sqrt{L})$

(Figures 3 and 4)

↓

C_P, C_X

↓

II4. L/B

(Tables 1 - 4)

↓

B

↓

II5. B/T

(Tables 1 - 4)

↓

T

↓

II6. **Final Check :** $\Delta_{FL} = \rho \bullet g \bullet C_P \bullet C_X \bullet L \bullet B \bullet T/2240$

Useful Output : $\Delta_{FL}, C_P, C_X, L, B, T, \Delta_L, C_V$

II. GROSS CHARACTERISTICS RELATIONSHIPS

II1. W_P = Given

Δ_{FL} = Pick

V_S = Given

II2. $\Delta_L = \Delta_{FL}/(0.01 \bullet L)^3$

II3. L = Pick

C_P=Pick

C_X=Pick

II4. B=Pick

II5. T=Pick

II6. g=Given

ρ=Given

$\nabla_{HV} = C_P \bullet C_X \bullet L \bullet B \bullet T$

$C_V = \nabla_{HV}/L^3$

Final Check: $\Delta_{FL} = \rho \bullet g \bullet C_P \bullet C_X \bullet L \bullet B \bullet T/2240$

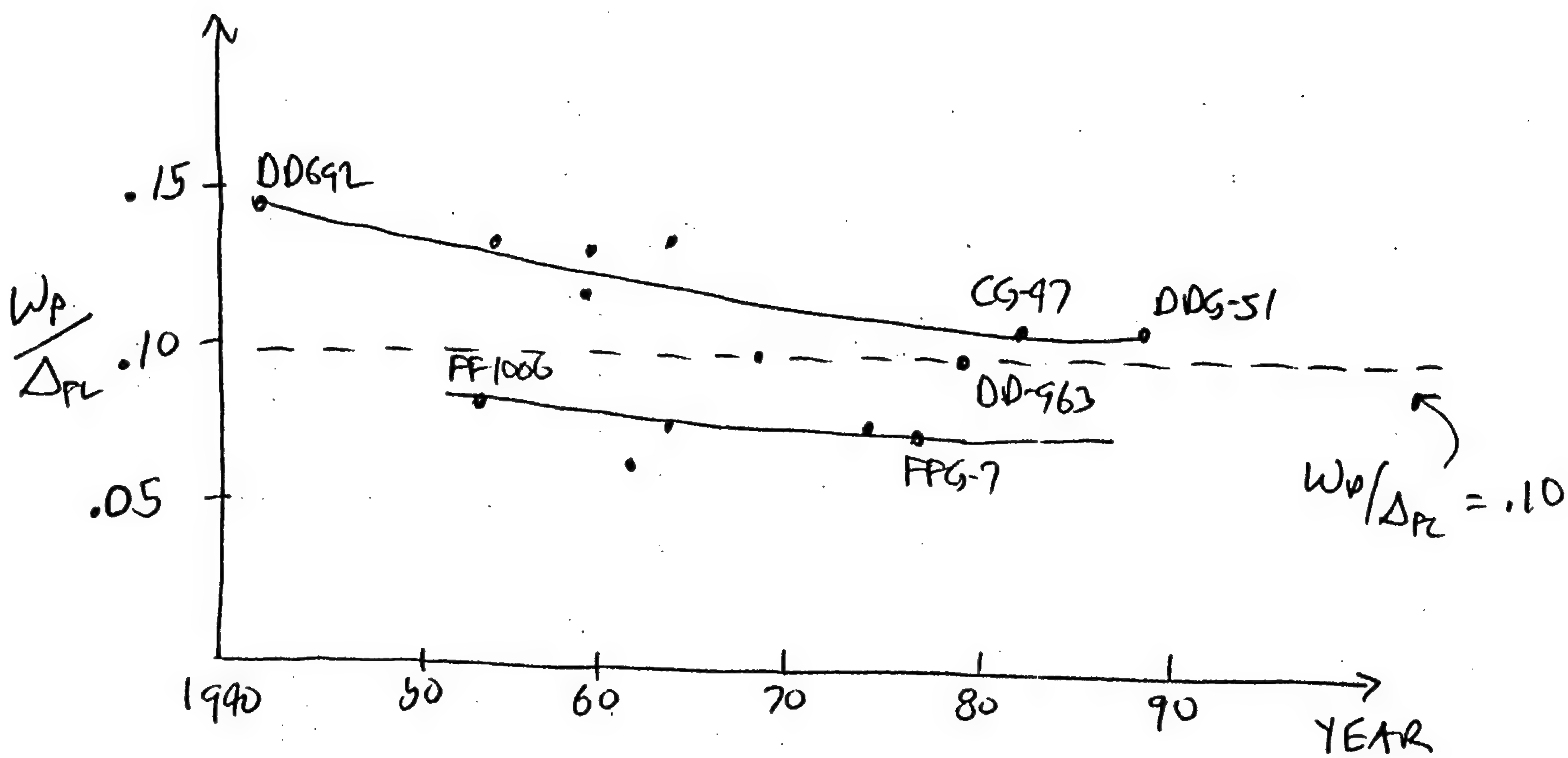


Fig. 1. PAYLOAD WEIGHT FRACTION

Fig 2

SPEED TREND

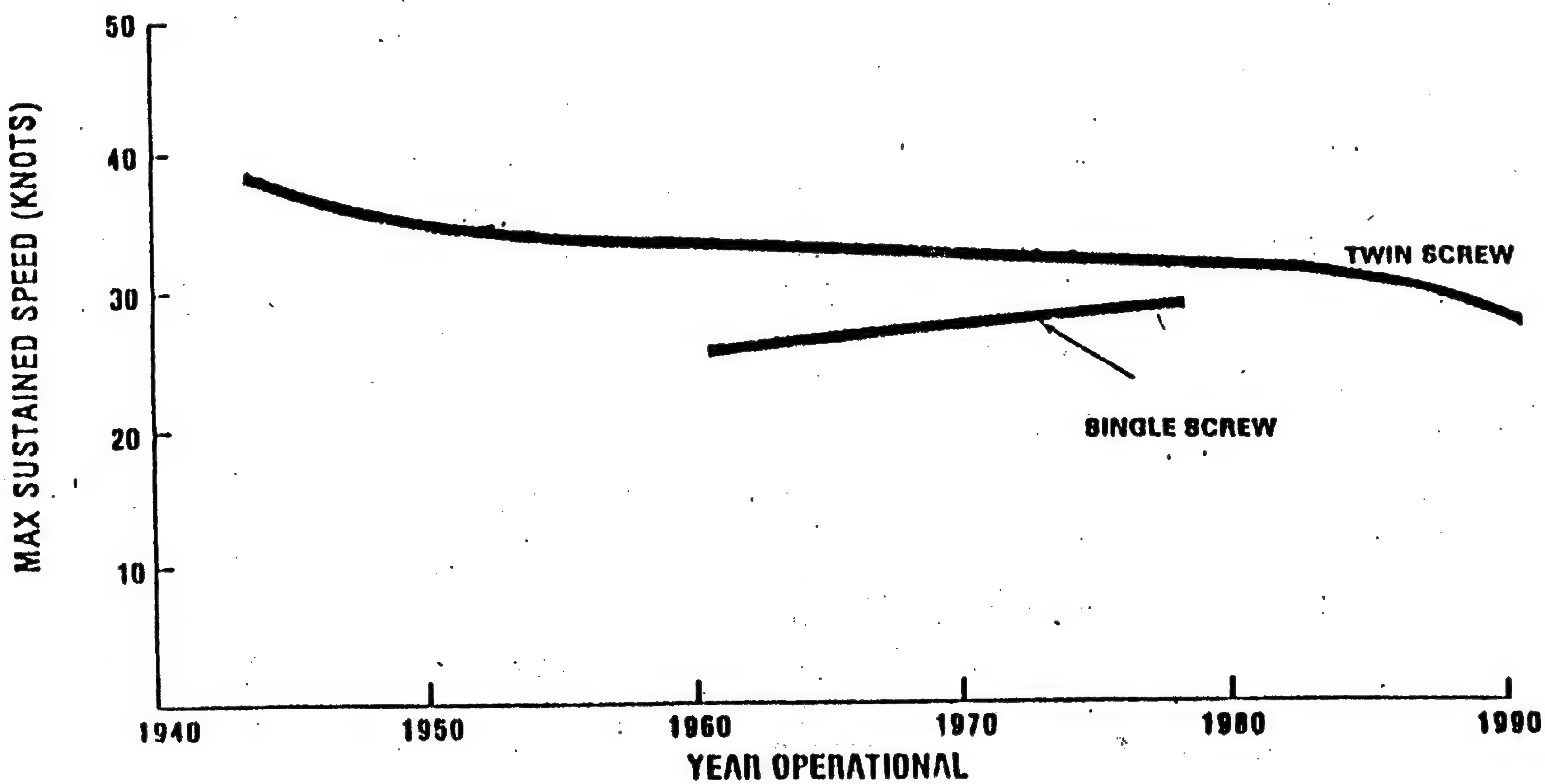
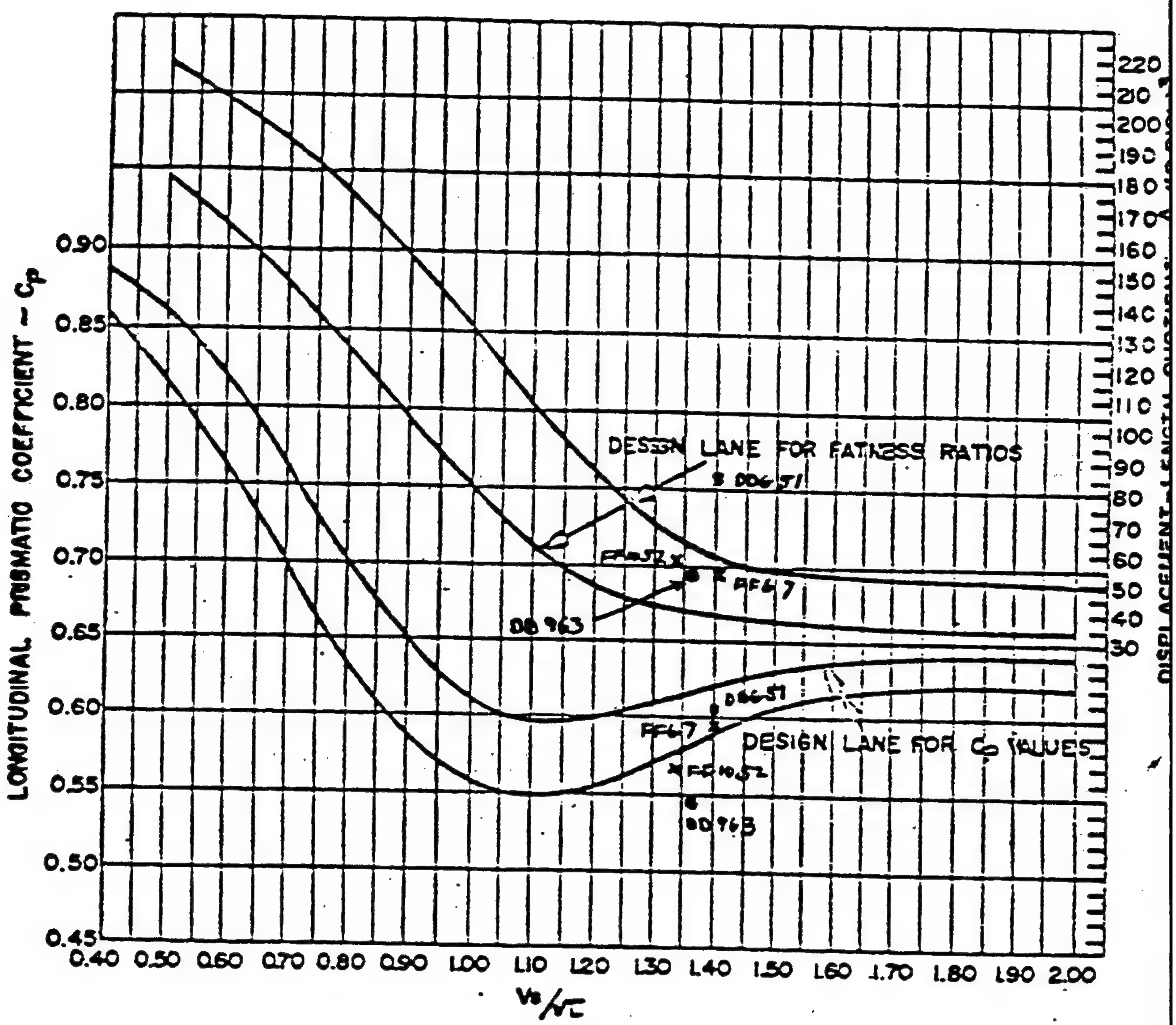


Fig 3

DESIGN LANES FOR ℄ + C_p

HYDRODYNAMICS IN SHIP DESIGN



52.1

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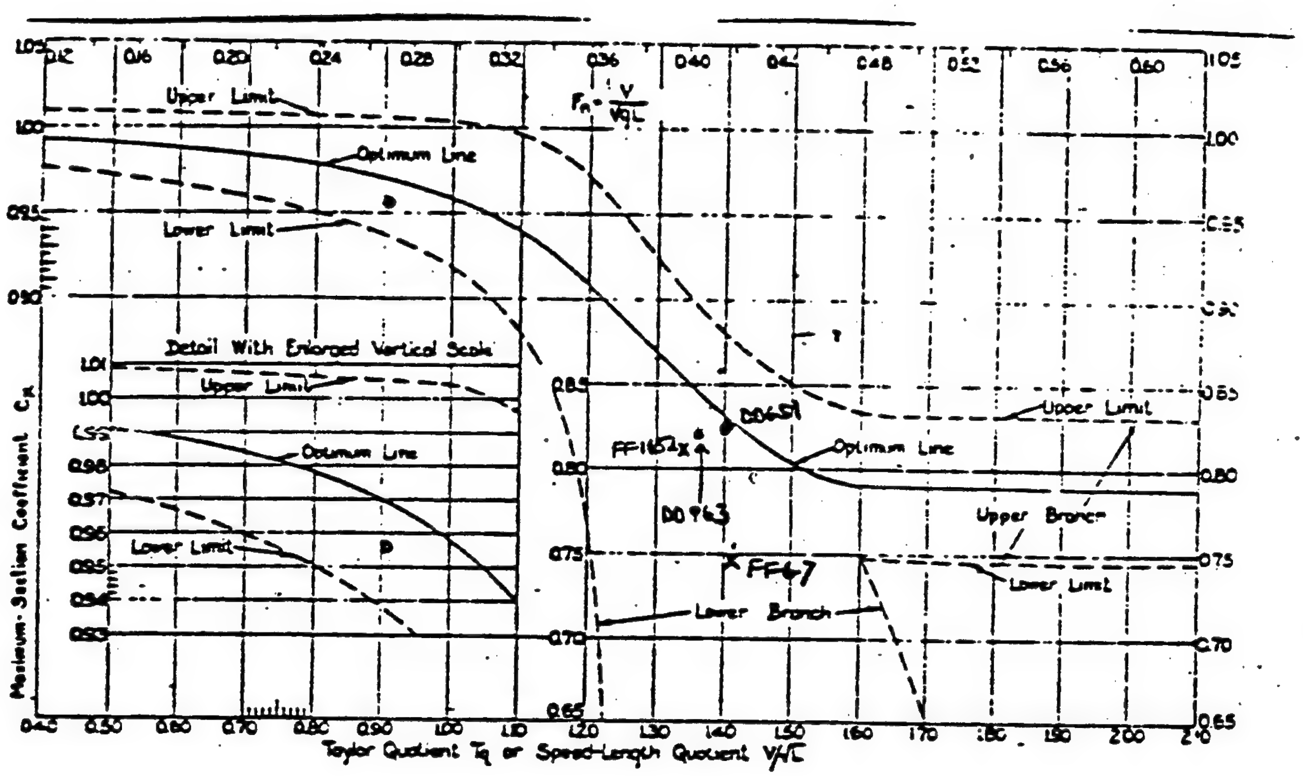
Ref. Saunders, Hydrodynamics in Ship Design. SNAME 1957 Vol II P 466

Fig 4

DESIGN LANES FOR MAXIMUM SECTION COEFFICIENT, C_x



Ref. Saunders
Vol II p 469

Table 1

VARIATION OF PARAMETERS FOR POST WWII U.S. NAVAL FRIGATE/ DESTROYER/CRUISER DESIGNS

PARAMETER	RANGE	FFG7	DD963*	DDG51
S	6.975-8.95	7.36	7.86	7.19
L/B	7.92-9.92	9.1	9.6	7.5
B/T	2.87-3.21	3.1	3.1	3.1
C_P	.56-.636	.593	.547	.604
C_x	.747-.835	.747	.823	.825
$\frac{\Delta}{L}$	43.4-65.6	49	46	81
L/D	10.75-17.81	13.6	12.6	11.1
GM/B	.0747-.1227			
$V/\sqrt{L}$	1.24-1.978	1.41	1.37	1.40
C_{WP}	.656-.795	.727	.727	.780
W_P/Δ	.0899-.1329	.08	.082	.11
Δ/VOL #/Ft^3	15.1-28.84			

*Data represents hull forms with a "no-dome" bow.

TABLE 2

Selected Characteristics* of Existing Frigates and Frigate Designs

Country	Ships	LWL (ft)	L/B	B/T	Cp	Cx	$\Delta/(0.01L)^3$
USA	DE 1006	308	8.4	3.0	0.60	0.80	65
	DE 1037	350	8.7	3.0	-	-	62
	DE 1040	390	8.9	3.0	0.61	0.80	58
	DE 1052	415	8.9	3.1	0.57	0.81	53
	FFG-7	408	9.1	3.1	0.59	0.75	49
	USCG Hamilton	350	8.3	3.1	0.58	0.83	63
U.K.	Leander	360	8.8	3.0	-	-	63
	Type 21	360	8.6	3.3	-	-	59
	Type 22	410	8.5	3.5	0.59	0.82	55
	Type 42	392	8.5	3.7	0.62	0.90	59
Canada	DDH 261	356	8.5	3.0	-	-	63
	DDH 280	398	7.9	3.2	-	-	73
France	C-67A	468	9.4	3.4	0.63	0.81	48
	C-70	423	9.3	3.4	0.63	0.81	49
	C-74						
Netherlands	G.M. Frigate	430	8.9	3.2	-	-	53
	Std. Frigate	400	8.6	3.3	0.59	0.78	55
Germany	Type 101	421	9.6	2.8	-	-	62
	Type 120	344	9.6	2.6	-	-	66
	Type 122	400	8.6	3.3	0.59	0.78	55
Norway	Oslo	308	8.5	3.2	-	-	60
Italy	Audace	432	9.1	3.1	-	-	55
	Lupo	348	9.0	3.2	0.63	0.79	49
	Maestrale	373			0.62	0.78	57
USSR	Krivak	384	8.8	2.8	0.62	0.80	62
	Kashin	440	9.0	3.2	0.62	0.86	58

*In some cases, values given are approximate; the data sources are, at times, confusing.

TABLE 3

Comparison of FFG 7 Secondary Hull Form Characteristics
and
Those Recommended for Small (3000-ton) Frigates

Parameter	FFG 7	Recommended for Minimum Resistance
Forward Section Shape	"UV"	Mild "V", or "UV"
A/A_x Curve Entrance	Very slightly "hollow"	Slightly "hollow"
t_E Taylor entrance parameter	-	≈ 0.90
Section Coefficient at Station 1.0	≈ 0.64	$\lesseqgtr$ 0.60
A_{20}/A_x	0.028	0.01 to 0.03
i_E Entrance half-angle	8.0°	6.7° to 8.7°
C_{WPF} Forebody waterplane coeff.	0.610	< 0.62
$\overline{FF}/LWL$	0.556	$\gtreqless$ 0.57
B_{20}/B_x	0.513	0.50 to 0.70
C_{VPF} Forebody vertical prismatic coeff.	0.720	$\gtreqless$ 0.70
C_{VPA} Afterbody vertical prismatic coeff.	0.650	$\gtreqless$ 0.58
Aft buttock shape	Almost straight	Little or no "hook"
C_{PA}/C_{WPA}	0.706	$\gtreqless$ 0.72

Taken from:
FFG-7 Review of Hydrodynamic Design and Performance
NAVSEA Report -3213-81-20
Sept 1981

TABLE 4 Primary Characteristics of Selected Destroyer-Type Hull Forms (Ordered by L_{PP})

Hull Form	L_{PP} (ft)	B_X (ft)	T_X (ft)	C_P*	C_X	$Displ_{DH}$*	L_{PP}/B_X	B_X/T_X	L_{PP}/T_X	L_{PP}/D_{10}	$Displ/(L/100)^3$*	C_{WP}
MCM (CD)	202.0	38.50	9.50	0.597	0.817	1,030	5.2	4.1	21.3	8.4	125	0.768
MCM (Q.1)	240.0	43.88	11.83	0.575	0.842	1,724	5.5	3.7	20.3	8.3	125	0.756
WHEC	255.0	37.90	13.00	0.588	0.766	1,615	6.7	2.9	19.6	10.9	97	0.768
DE 356	300.0	35.5	10.00	0.620	0.811	1,530	8.5	3.6	30.0	15.0	57	-
DE 1006	308.0	36.50	12.10	0.604	0.803	1,890	8.4	3.0	25.5	15.0	65	0.754
DE 1037	350.0	40.32	13.50	0.580	0.801	2,530	8.7	3.0	25.9	11.8	59	0.721
DE, SCB 199	350.0	39.60	13.00	0.573	0.778	2,297	8.8	3.0	26.9	11.7	54	0.710
DD 692	369.0	40.59	13.00	0.616	0.827	2,833	9.1	3.1	28.4	16.0	56	0.745
Maestrale	374.0	41.01	12.80	0.620	0.780	2,712	9.1	3.2	29.2	13.7	52	0.764
FY 61 DE	375.0	40.40	13.80	0.584	0.781	2,731	9.3	2.9	27.2	12.5	52	0.710
DD 710	383.0	40.59	13.00	0.634	0.815	2,982	9.4	3.1	29.5	16.7	53	0.754
Krivak	383.6	43.31	14.76	0.610	0.820	3,506	8.9	2.9	26.0	11.7	62	0.774
FF 1040	390.0	43.70	14.50	0.580	0.794	3,245	8.9	3.0	26.9	13.0	55	0.728
Type 42	392.1	45.93	12.14	0.620	0.900	3,486	8.5	3.8	32.3	13.5	58	0.760
Work Study DE	395.0	44.50	14.20	0.562	0.823	3,290	8.9	3.1	27.8	-	54	0.723
STD Frigate	399.6	47.25	13.65	0.612	0.744	3,353	8.5	3.5	29.3	13.4	53	0.720

* For ships/designs which had a bow-mounted sonar dome, this data represents such hull forms with a "no-dome" bow.

TABLE 4 (Continued)

Hull Form	L_{PP} (ft)	B_X (ft)	T_X (ft)	C_P*	C_X	$Displ_{DH}$*	L_{PP}/B_X	B_X/T_X	L_{PP}/T_X	L_{PP}/D_{10}	$Displ/(L/100)^3$*	C_{WP}
DD 931	407.0	44.38	14.50	0.630	0.828	3,901	9.2	3.1	28.1	16.1	58	0.768
FFG 7	408.0	45.00	14.30	0.593	0.747	3,336	9.1	3.1	28.5	13.6	49	0.727
PFC	410.1	48.23	14.21	0.610	0.800	3,918	8.5	3.4	28.9	13.3	57	0.770
FF 1052	415.0	46.50	15.00	0.569	0.812	3,028	8.9	3.1	27.7	14.4	54	0.734
DDG 2	420.0	47.00	15.00	0.634	0.835	4,477	8.9	3.3	28.0	16.8	60	0.760
C70	423.3	45.93	13.45	0.620	0.793	3,673	9.2	3.4	31.5	14.1	48	0.753
DDGX	433.1	54.06	17.05	0.601	0.847	5,807	8.0	3.2	25.4	13.1	72	0.784
DDG 51 (6.1)	465.9	62.00	20.00	0.604	0.825	8,229	7.5	3.1	23.3	11.1	81	0.780
DL 2	476.0	48.00	14.04	0.611	0.801	4,480	9.9	3.4	33.9	16.9	42	0.746
DLG 9	490.0	50.13	15.75	0.562	0.768	4,775	9.7	3.2	31.1	16.2	41	0.712
FTFE	490.0	49.90	15.80	0.560	0.771	4,770	9.8	3.2	31.0	16.3	41	0.710
CG 16	510.0	53.00	16.50	0.585	0.810	6,041	9.6	3.2	30.9	13.2	46	0.720
DL 1	520.0	53.77	17.62	0.566	0.808	6,435	9.7	3.1	29.5	15.1	46	0.703
CG 26	524.6	54.40	18.80	0.604	0.818	7,561	9.6	2.9	27.9	13.6	53	0.740
DDG FY 67	525.0	61.00	18.25	0.560	0.831	7,780	8.6	3.3	28.8	11.5	54	0.710
DD 963	529.0	55.00	18.00	0.547	0.823	6,731	9.6	3.1	29.4	12.6	46	0.727
DLG(N) 25	540.0	56.86	18.50	0.584	0.794	7,527	9.5	3.1	29.2	13.3	48	0.744

* For ships/designs which had a bow-mounted sonar dome, this data represents such hull forms with a "no-dome" bow.

TABLE 4 (Concluded)

Hull Form	L_{pp} (ft)	B_X (ft)	T_X (ft)	C_P*	C_X	$Displ_{DH}$*	L_{pp}/B_X	B_X/T_X	L_{pp}/T_X	L_{pp}/D_{10}	$Displ/(L/100)^3$*	C_{WP}
CGN 35	540.0	57.03	20.30	0.614	0.818	8,999	9.5	2.8	26.6	13.3	57	0.760
CGN 38	560.0	61.85	20.50	0.623	0.808	10,210	9.1	3.0	27.3	13.2	58	0.767
CGN 42	560.0	62.50	22.00	0.629	0.845	11,695	9.0	2.8	25.5	13.2	67	0.776
CGN 36	570.0	60.00	20.50	0.603	0.810	9,783	9.5	2.9	27.8	13.9	53	0.760
DLGN (TYPHON)	600.0	62.80	20.50	0.568	0.845	10,595	9.6	3.1	29.3	–	49	0.730
CSGN (Conv.)	666.0	76.70	22.15	0.582	0.897	16,885	8.7	3.5	30.1	15.7	57	0.736
CSGN (VSTOL)**	666.0	80.77	26.60	0.578	0.901	21,308	8.2	3.0	25.0	–	72	0.792
CGN 9	691.8	71.00	21.50	0.578	0.807	14,080	9.7	3.3	32.2	15.4	43	0.710
CA 139	700.0	74.80	24.00	0.616	0.868	19,200	9.4	3.1	29.2	17.6	56	0.745

Note

The hull form characteristics listed in this table are, in some cases, based on the hull form up to the DWL and, in other cases, based on the hull form up to a particular waterline near to, but other than, the DWL (e.g., in some cases the characteristics apply to the hull form up to a waterline at which the hull was model tested) or up to a waterline representing the ship draft in the full-load condition.

* For ships/designs which had a bow-mounted sonar dome, this data represents such hull forms with a "no-dome" bow.

** Hull form was based on that of the Large-Waterplane version of the CSGN design.

Table 5

NAVIGATIONAL RESTRICTIONS

	Draft (ft)	Length (ft)	Be
A. Ports			
Baltimore, Maryland	23-40	600-810	
Baton Rouge, Louisiana	40	no limit	
Beaumont, Texas	34	600-760	
Boston, Massachusetts	30-38	575-1200	
Brownsville, Texas	34.5	no limit	
Charleston, S. Carolina	30-35	600-705	
Chicago, Illinois	27		
Eureka, California	10-31	200-500	
Freeport, Texas	36	670	
Gulfport, Mississippi	30-32	700	
Hampton-Roads, Virginia	15-38		
Houston, Texas	30-40	600	
Jacksonville, Florida	31-36	600	
Long Beach, California	54	1200	
Los Angeles, California	35-51	226-1895	
New York, New York	20-40	170-1280	
Providence, Rhode Island	34	600	
San Francisco, California	25	300	
B. Canals			
Panama	38.5	835	104
C. Drydocks			
Long Beach Naval Shipyard		1092	144
Norfolk Naval Shipyard		1092	143
National Steel & Shipbuilding Corp., San Diego, CA		965	170
Newport News Shipbuilding and Drydock Corp., Newport News, Virginia		1600	230

III.ENERGY (Use enclosures 4 and 5 to calculate energy needs)

Input: Δ_{FL},L,B,T,C_P,C_X,Δ_L,(C_V),V_S,V_e,E,FR,FR_G,kW_{24},PC,W_{LO}

↓

III1. V_S,V_e
Taylor Series
ITTC
$C_A = 0.0005$
(Figure 1)

↓

EHP_{BHT} at V_S and V_e

↓

III2. Worm Curve
(Figures 3 - 8)

↓

EHP_{BH} at V_S and V_e

↓

II3. Appendage Allowance
(Figures 9 -10)

↓

EHP at V_S and V_e

↓

III4. PC

↓

SHP at V_S and V_e (P_S,P_e); P_I

↓

III5. E,V_e,P_e,FR

↓

W_{FP}

↓

III6. Combat Systems
N_T, P_1, CN

↓

kW_{24},KW_I

↓

III7. $FR_{avg\ e}$

↓

III8. W_{Fe}
W_F

↓

Useful Output : P_S, P_e, P_I, kW_{24avg}, kW_I,W_F

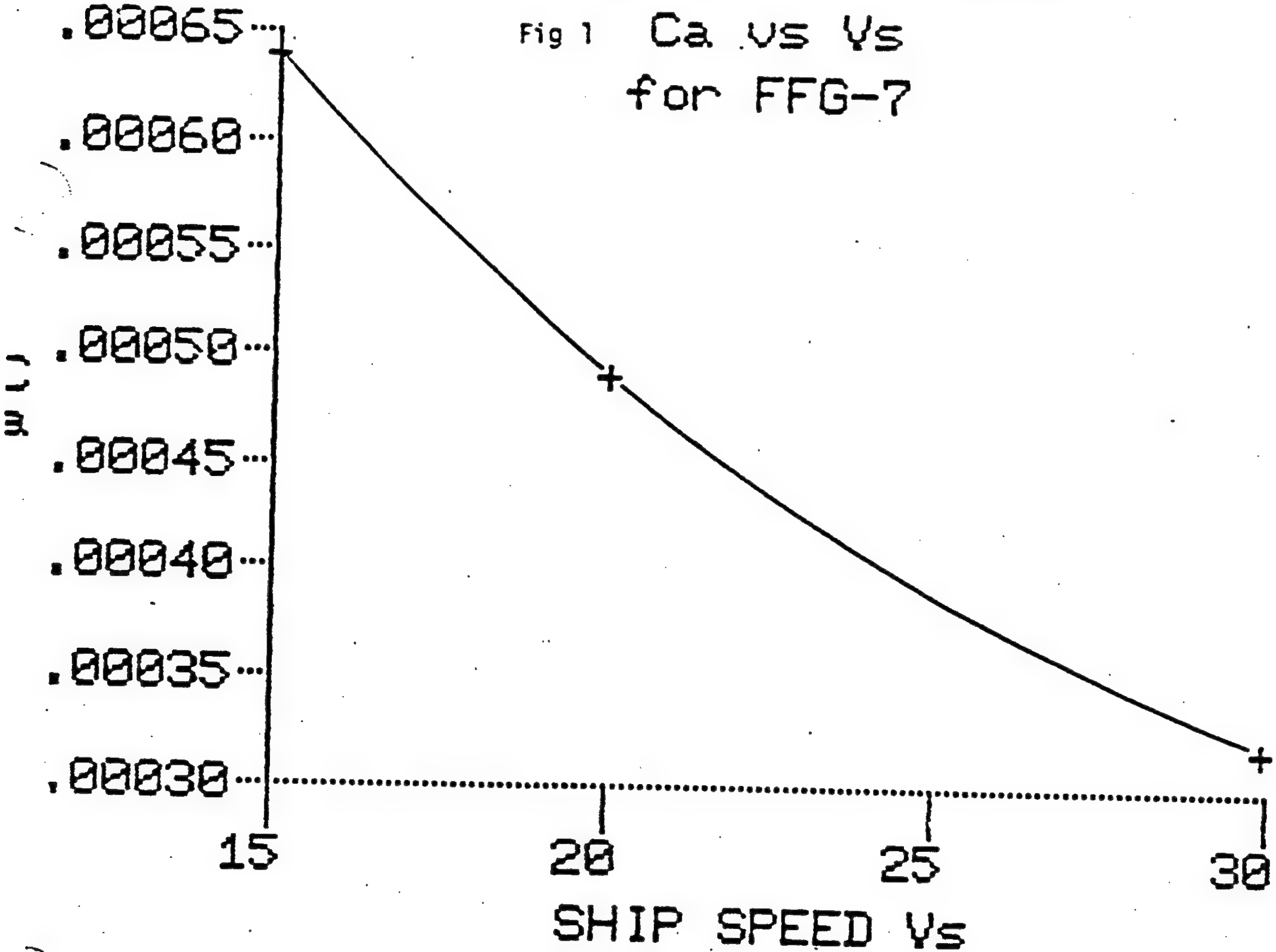


Fig 1 Ca vs Vs for FFG-7

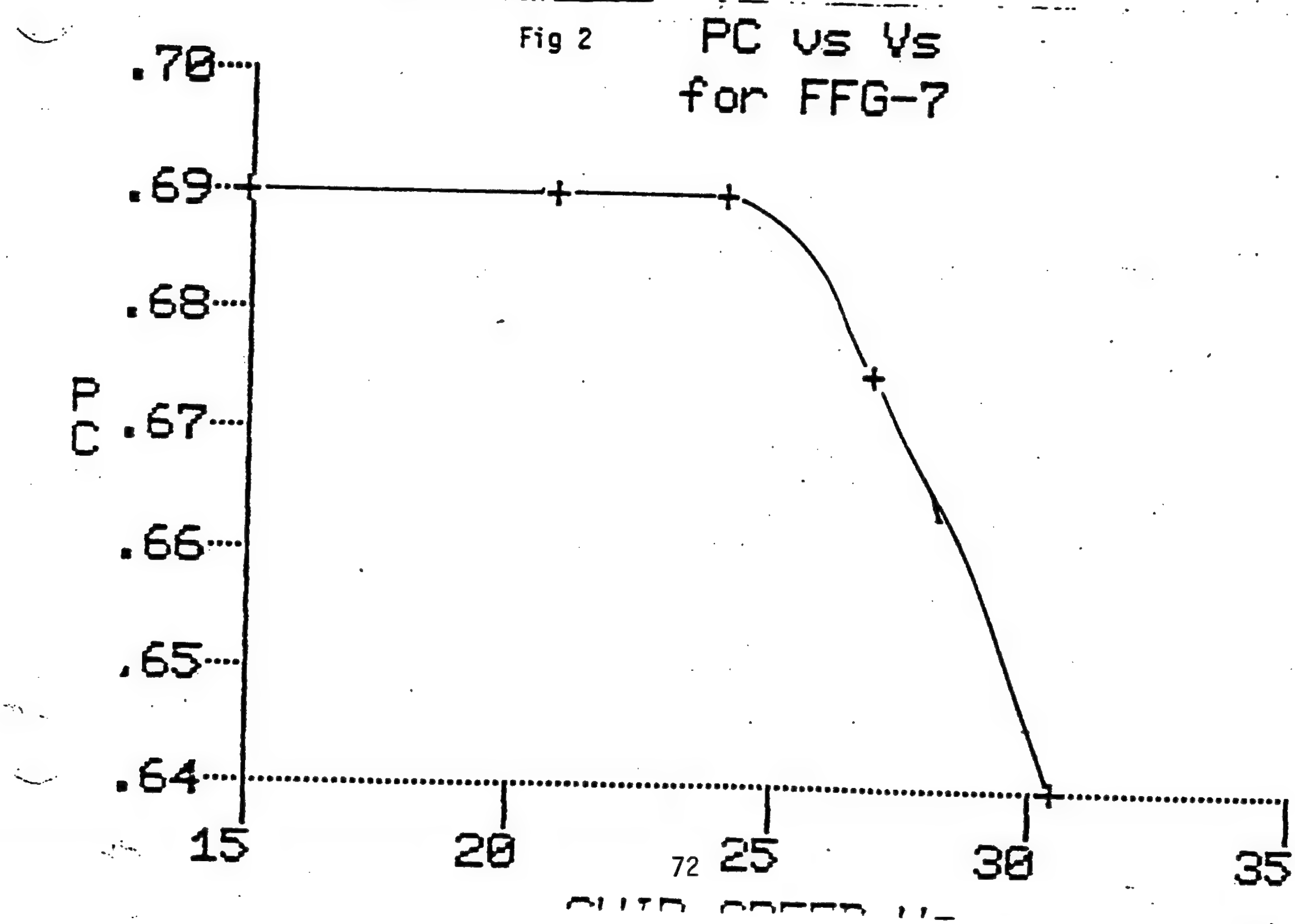


Fig 2 PC vs Vs for FFG-7

IV. SPACE

Input: $L, B, T, C_P, C_x, L_{MB}, H_{MB}$, Liquid Densities, W_F, W_{LO}, W_{HF}, N_T
$A_{HPA}, A_{HPC}, A_{DPA}, A_{DPC}, EP_{DRY}, EP_{CHL}, EP_{FRZ}, EP_{GSM}, f_{MB}$

A. Available

L, B, T, C_P, C_x
↓
IVA1. Underwater Hull Volume
∇_{HV}
↓
IVA2. H_{MB}
Depth Functions
↓
Sheer Line
(D_0, D_{10}, D_{20})
↓
IVA3. F_0, F_{10}, F_{20}
D_{AV}
↓
CN
Above Water Volume
∇_{HAW}
Total Hull Volume
∇_{HT}
↓
IVA4. Deck House Criteria
↓
Deck House Volume Available
∇_D
Total Ship Volume Available
∇_T

B. Required

$L, B, T, C_P, D_{MB}, A_{MB}, L_{MB}$(pick), H_{MB}, f_{MB}

$\downarrow$

IVB1. $C_{PMB} = f(C_P, L_{MB}/L)$

$\downarrow$

∇_{MB}

$\downarrow$

IVB2. Liquid Weights
Liquid Densities

$\downarrow$

∇_{TK}

$\downarrow$

IVB3. Payload Areas

$\downarrow$

A_{HPR} , A_{DPR}

$\downarrow$

IVB4. N_T , L

$\downarrow$

A_{HL} , A_{DL}

$\downarrow$

IVB5. Endurance Periods

$\downarrow$

A_{HS}

$\downarrow$

IVB6. A_{DPR} , A_{DL} , B, CN

$\downarrow$

IVB7. A_{HSF} , A_{DSF}

Total Required Deck House Arrangement Area

A_{DR}

Total Required Hull Arrangement Area

A_{HR}

C. Balance

IVC1.

∇_{TK} ,∇_{MB} , ∇_{HT}

↓

Hull Arrangement Volume Available

∇_{HA}

↓

IVC2.

Hull and Deck House
Arrangement Area Available

H_T ,∇_{HA} , ∇_D

↓

A_{HA} , A_{DA}

↓

IVC3.

Compare A_{HR} and A_{HA}
Compare A_{DR} and A_{DA}

Useful Output : Machinery box dimensions, deck areas for functions in deck house and hull, tankage volumes and total ship volumes

IV. SPACE ESTIMATING RELATIONSHIPS

A. Available

IVA1. $\nabla_{HV}=L\bullet B\bullet T\bullet C_P\bullet C_X$

IVA2.

$$F_{10R} \geq 0.21\ B$$
$$D_{10R} = F_{10R} + T$$
$$D_{10MB} \geq H_{MB}$$
$$D_{10BC} \geq L/15$$

Select D_{10} as largest of D_{10R} , D_{10MB} , D_{10BC}

$$D_0 \geq 1.011827\bullet T - 6.36215 \times 10^{-6}\bullet L^2 + 2.780649 \times 10^{-2}\bullet L + T$$
$$D_{20} \geq .01\bullet L\bullet(2.125 + 1.25 \times 10^{-3}\bullet L) + T$$

Draw faired line through D_0, D_{10} and D_{20} and submit with report

IVA3.

$$F_0 = D_0 - T;\ F_{10} = D_{10} - T;\ F_{20} = D_{20} - T$$
$$A_{PRO} = L\bullet(F_0 + 4\bullet F_{10} + F_{20}) / 6$$
$$F_{AV} = A_{PRO} / L$$
$$D_{AV} = F_{AV} + T$$
$$CN = L\bullet B\bullet D_{AV} \times 10^{-5}$$
$$C_W = 0.236 + 0.836\bullet C_P$$
$$f_f = 0.714599 + 0.18098\bullet D_{AV}/T - 0.018828\bullet(D_{AV}/T)^2$$
$$\text{If } f_f < 1.0 \text{ then use } f_f = 1.0$$
$$\nabla_{HAW} = L\bullet B\bullet F_{AV}\bullet C_W\bullet f_f$$

IVA4. $\nabla_{HT} = \nabla_{HV} + \nabla_{HAW}$

IVA5. Deck house sizing : $0.001\ L^3 < D_{10} < 0.0015\ L^3$

IVA6. $\nabla_T = \nabla_{HT} + \nabla_D$

B. Required

IVB1. $C_{PMB} = f(C_P, L_{MB}/L)$
(Use figure 2 for data, 3 and 4 for comparison)
$D_{MB} \approx H_{MB}$

$A_{MB} = B \bullet T \bullet C_x + B \bullet (D_{MB} - T)$
f_{aux} = given
$\nabla_{MB} = L_{MB} \bullet A_{MB} \bullet C_{PMB}$
$\nabla_{aux} = \nabla_{MB} \bullet f_{aux}$

IVB2. $W_W = 0.224\ N_T$
$\nabla_{TK} = K_1 \bullet K_2 \bullet (W_F \bullet \gamma_F + W_{HF} \bullet \gamma_{HF} + W_{LO} \bullet \gamma_{LO}) + K_1 \bullet W_W \bullet \gamma_W + \nabla_{void}$
where: K_1 = factor for structure, 1.02
K_2 = factor for expansion, 1.05
γ_F = given
γ_{HF} = given
γ_{LO} = given
γ_W = given

IVB3. $A_{DPR} = 1.15 \bullet A_{DPA} + 1.23 \bullet A_{DPC}$
$AHPR = 1.15 \bullet A_{HPA} + 1.23 \bullet A_{HPC}$
where 1.15 and 1.23 are allowances for access

IVB4. $A_{DL} = 400\ ft^2$ (for Commanding Officer)
$A_{HAB} = 48\ ft^2/man$
$A_{HL} = (A_{HAB} + L/100)\ N_T - A_{DL}$
valid for $150 < N_T < 500$
and $.06 < N_O/N_T < .091$

IVB5. $A_{HS} = 300 + 0.0158 \bullet N_T \bullet (2 \bullet EP_{DRY} + 2 \bullet EP_{CHL} + EP_{FRZ} + 4 \bullet EP_{GSM})$

IVB6. $A_{DM} = 0.15\ A_{DPR} + 0.15\ A_{DL}$
$A_{DB} = 16\ (B - 18) + 80$
$A_{DSF} = A_{DM} + A_{DB}$
$A_{HSF} = 2140 \bullet CN - 540$

IVB7. $A_{HR} = A_{HPR} + A_{HL} + A_{HS} + A_{HSF} + (I_{VH} / H_T)$
$A_{DR} = A_{DPR} + A_{DL} + A_{DSF} + H_A + (I_{VD} / H_T)$
$A_{TR} = A_{HR} + A_{DR}$
$\nabla_{DR} = H_T \bullet A_{DR}$
$\nabla_{HR} = H_T \bullet A_{HR}$
$\nabla_{TR} = \nabla_{DR} + \nabla_{HR}$

C. Balance

IVC1. $\nabla_{HA} = \nabla_{HT} - \nabla_{MB} - \nabla_{aux} - \nabla_{TK}$
$\nabla_{TA} = \nabla_{HA} + \nabla_{D}$

IVC2. $A_{HA} = \nabla_{HA} / H_T$
$A_{DA} = \nabla_{D} / H_T$

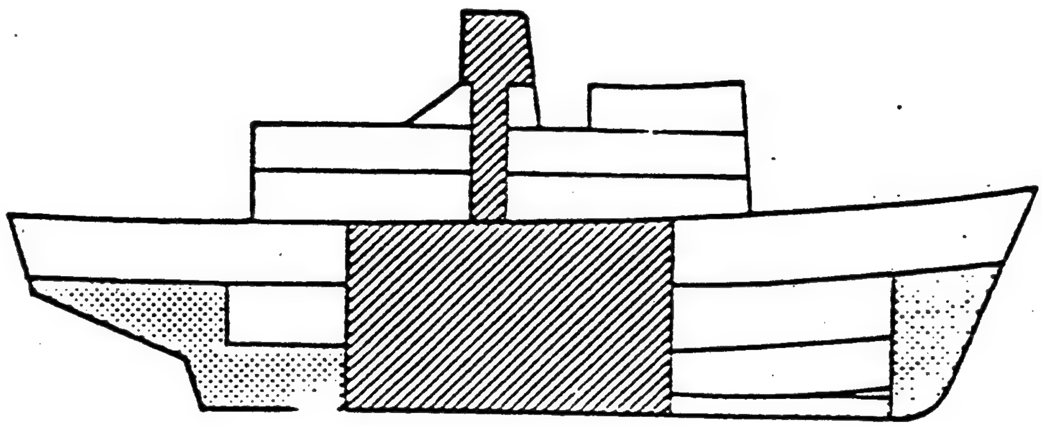
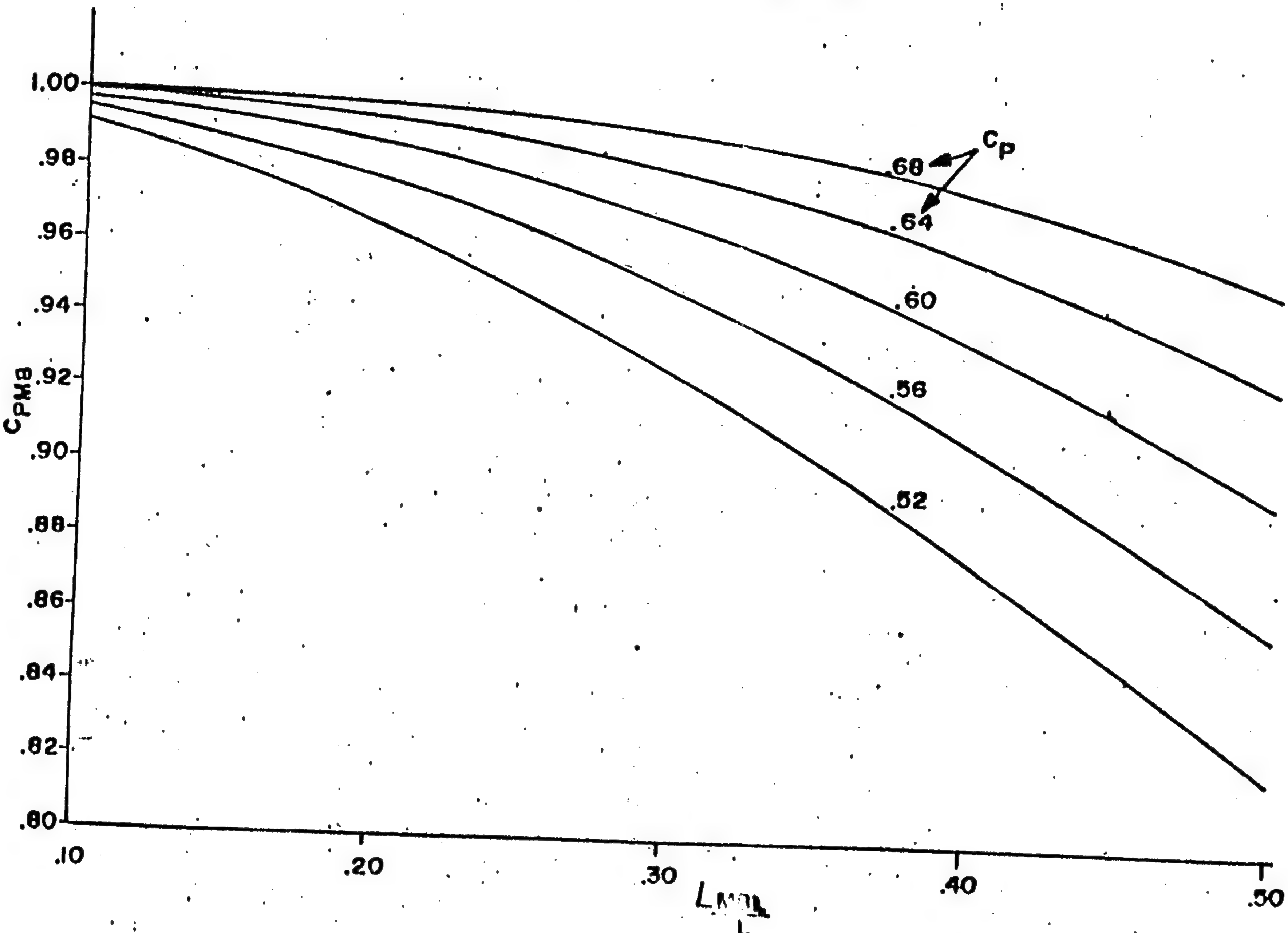


Figure 1 Relationship Among the Three Types of Space

Fig 2 Machinery Box Prismatic Coefficient



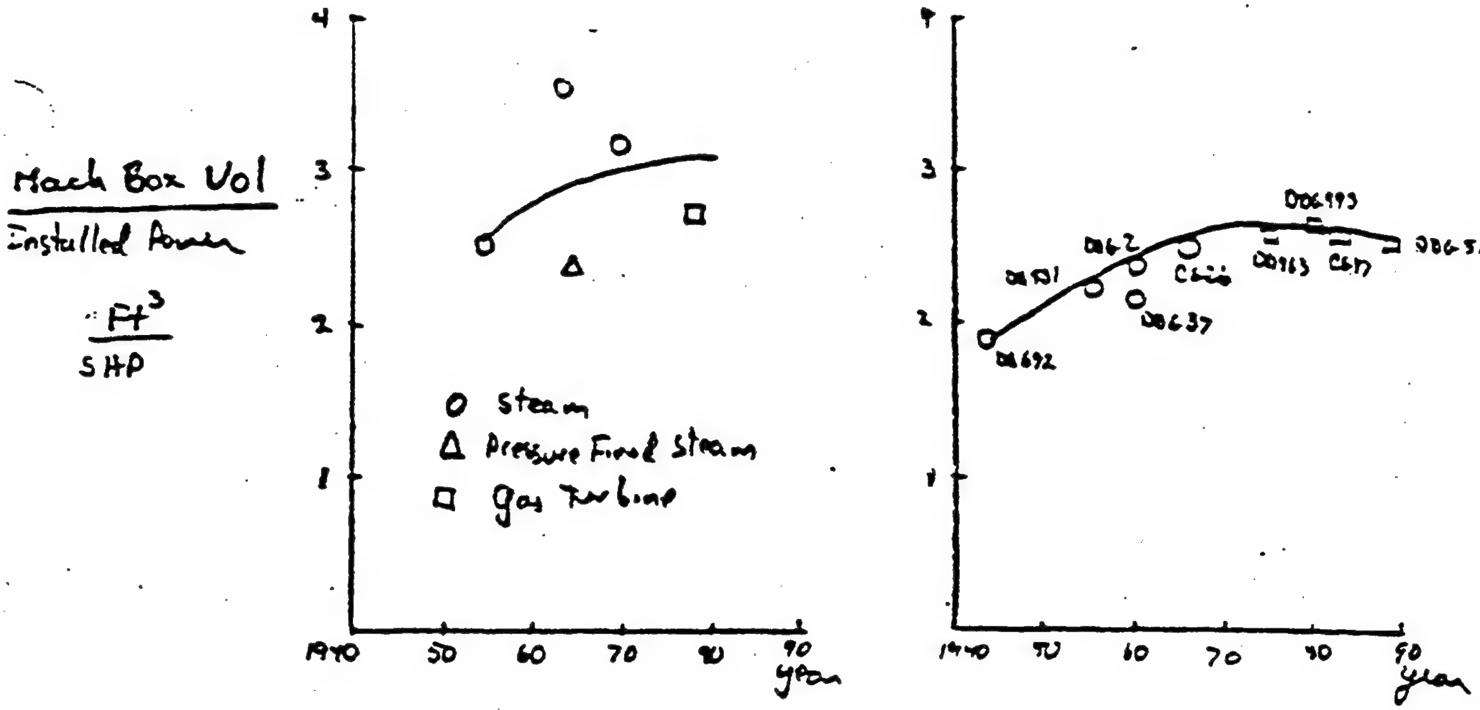


Fig 3 Machinery Box Volume

Fig 4 FRIGATES – SPECIFIC MACHINERY VOLUME

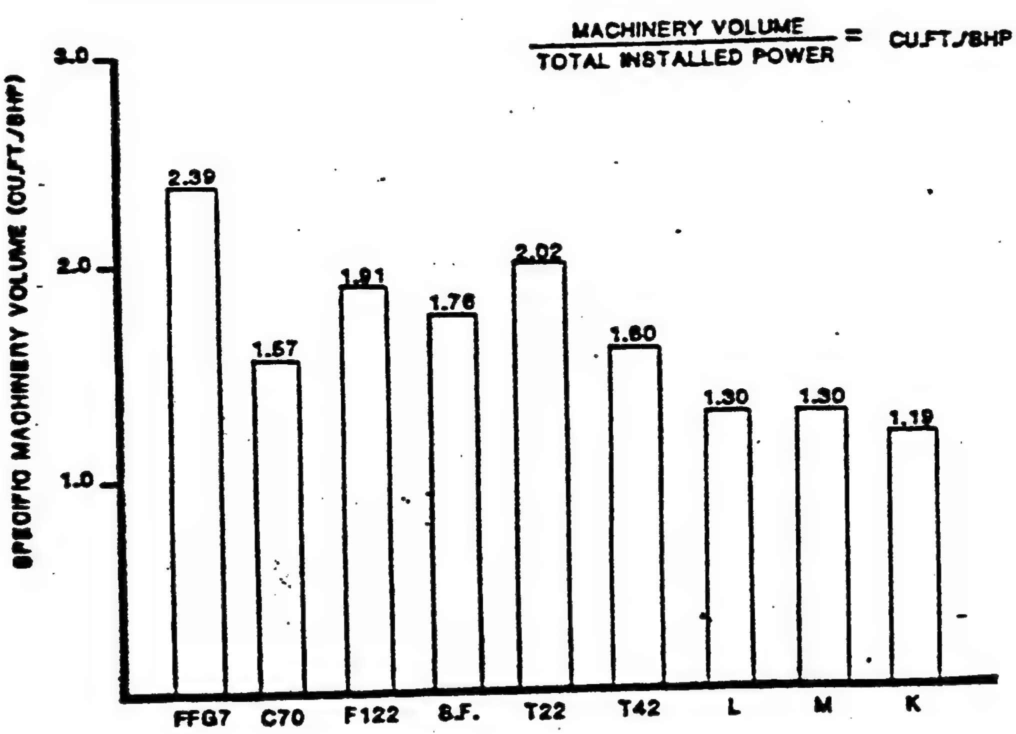


Fig 5

PAYLOAD TREND

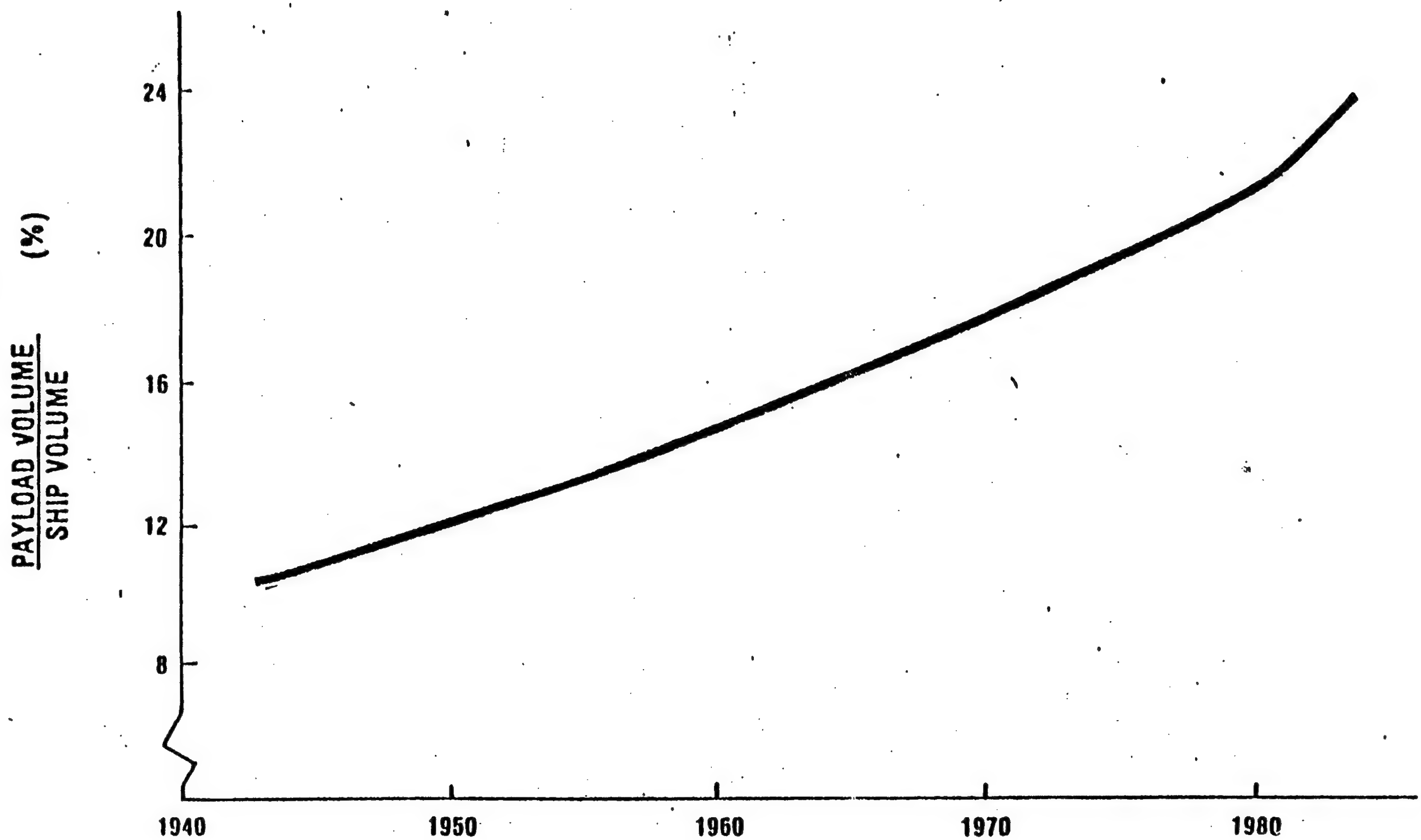


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Fig 6 FRIGATES - PAYLOAD VOLUME

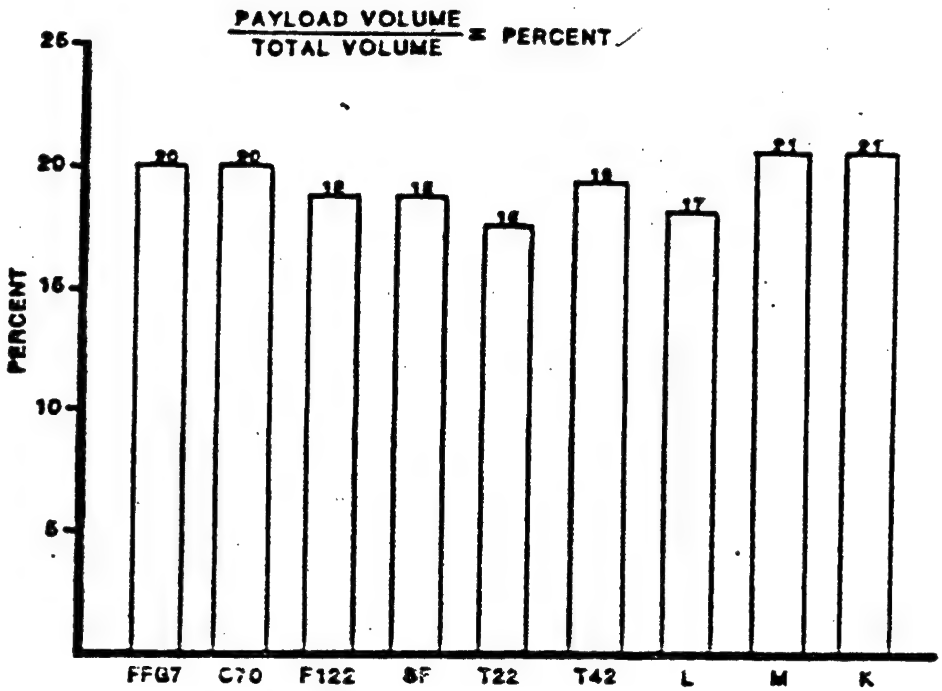


Fig 7 PAYLOAD VOLUME - U.S. SHIPS

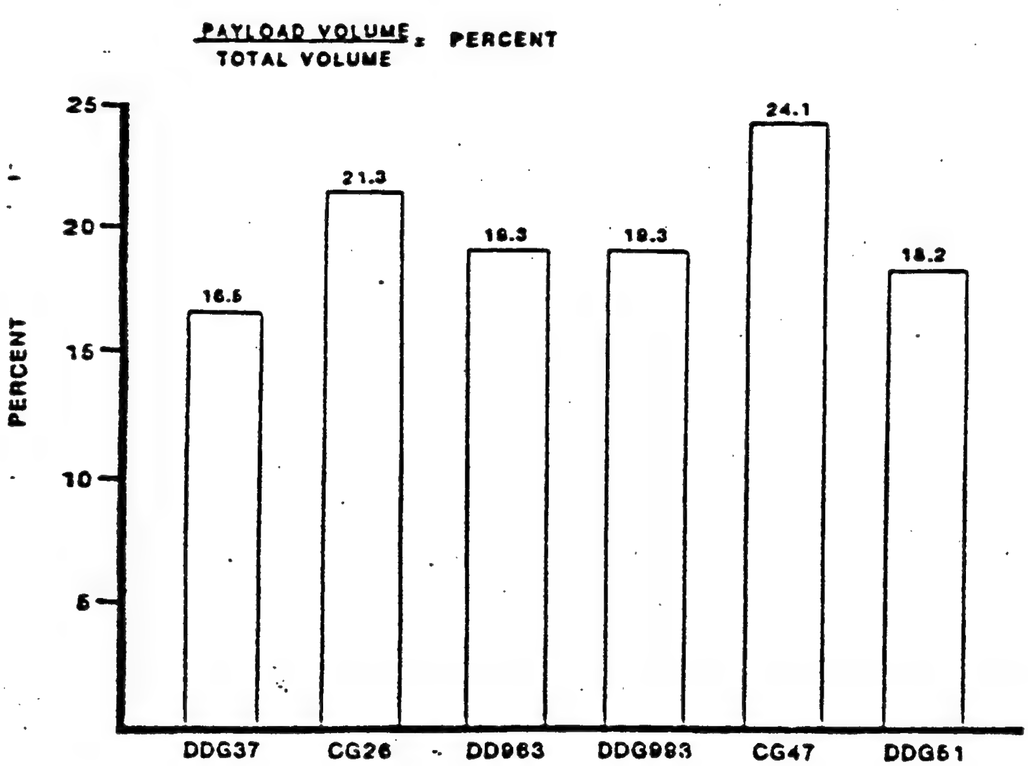
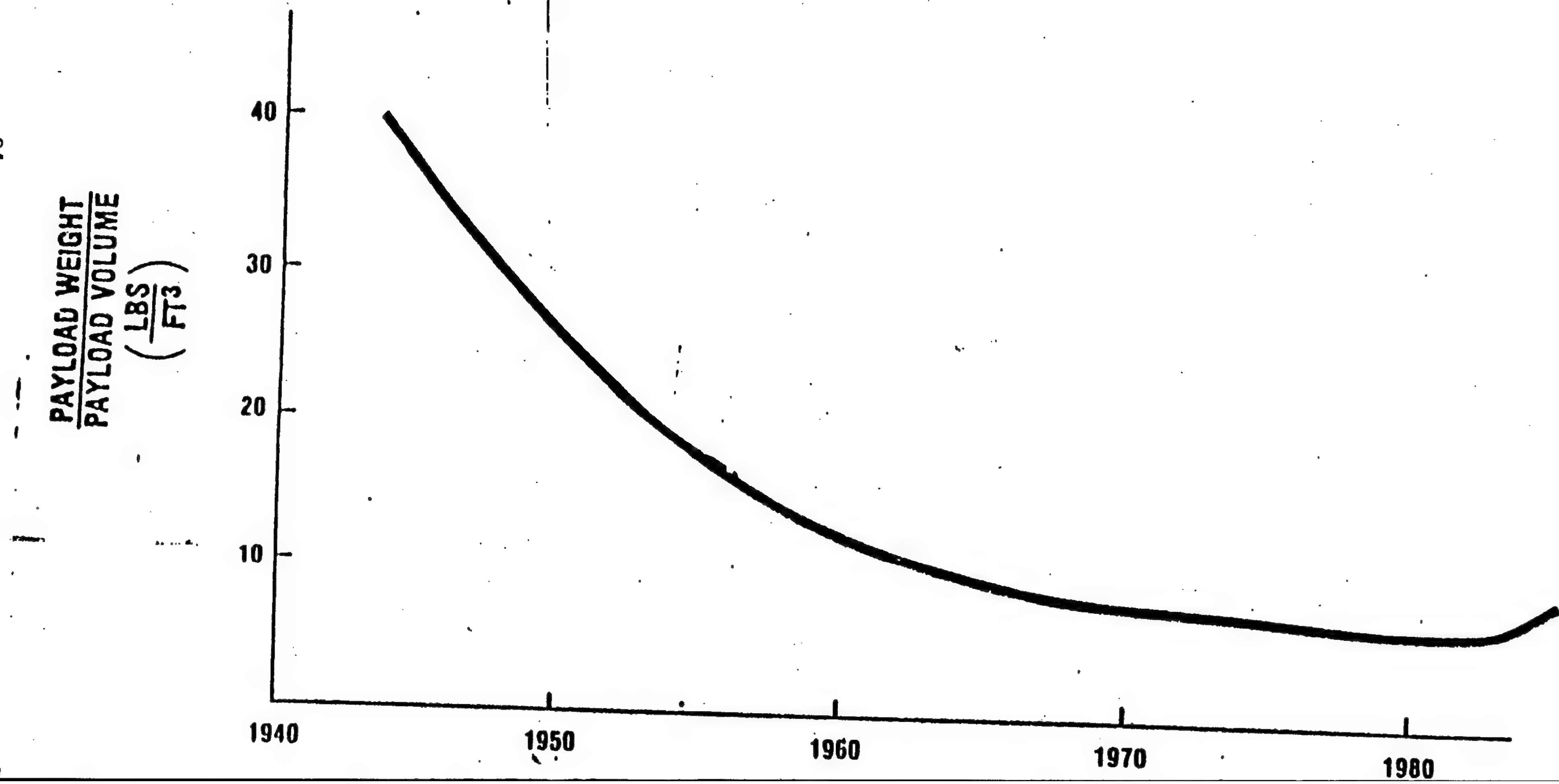


Fig 8 **PAYLOAD TREND**



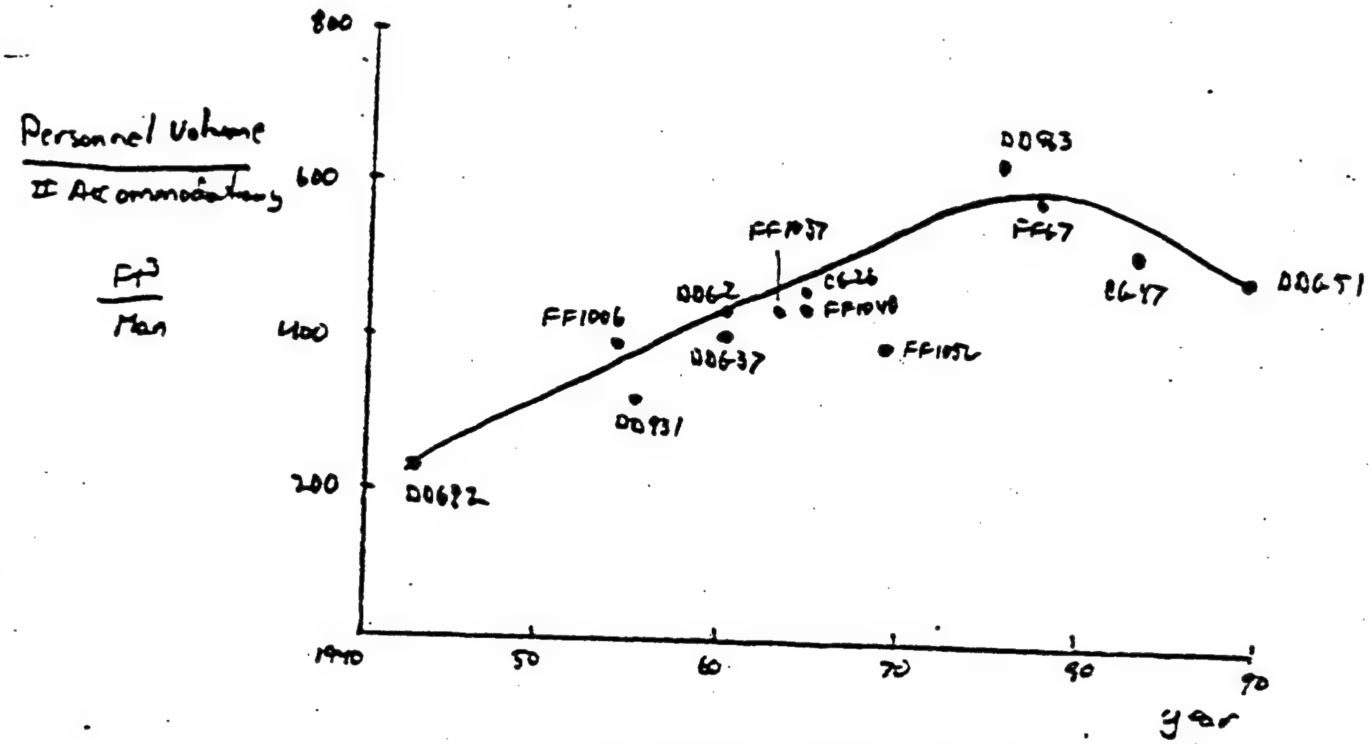


Fig 9 Personnel Volume

Fig 10 HABITABILITY DECK AREA - U.S. SHIPS

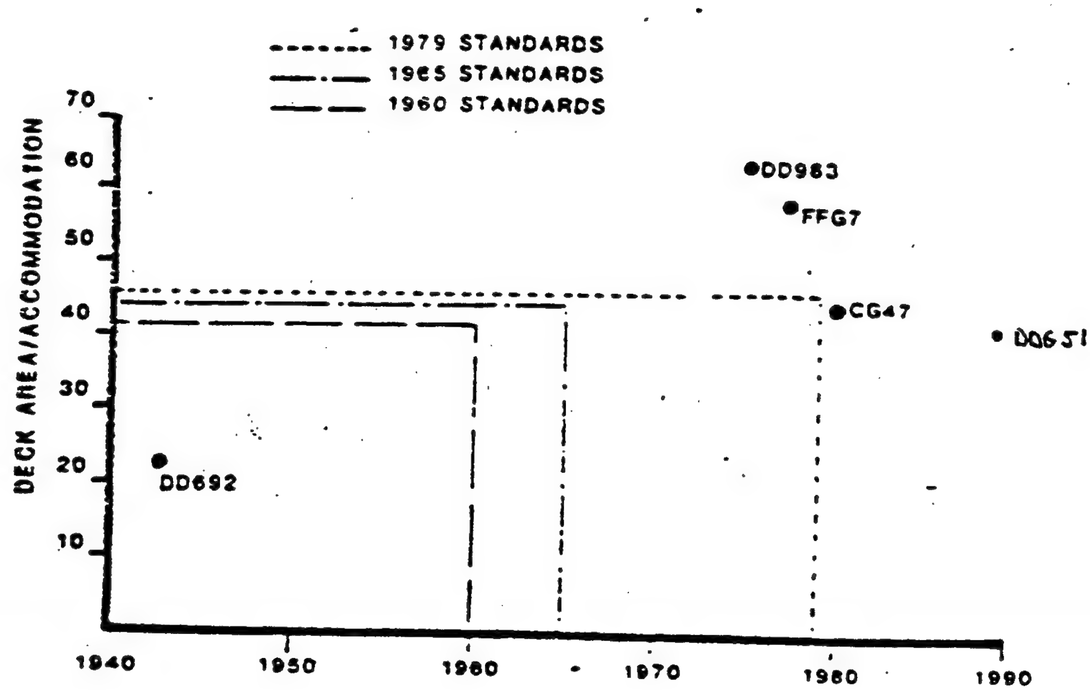


Fig 11 FRIGATES – HABITABILITY SPACE

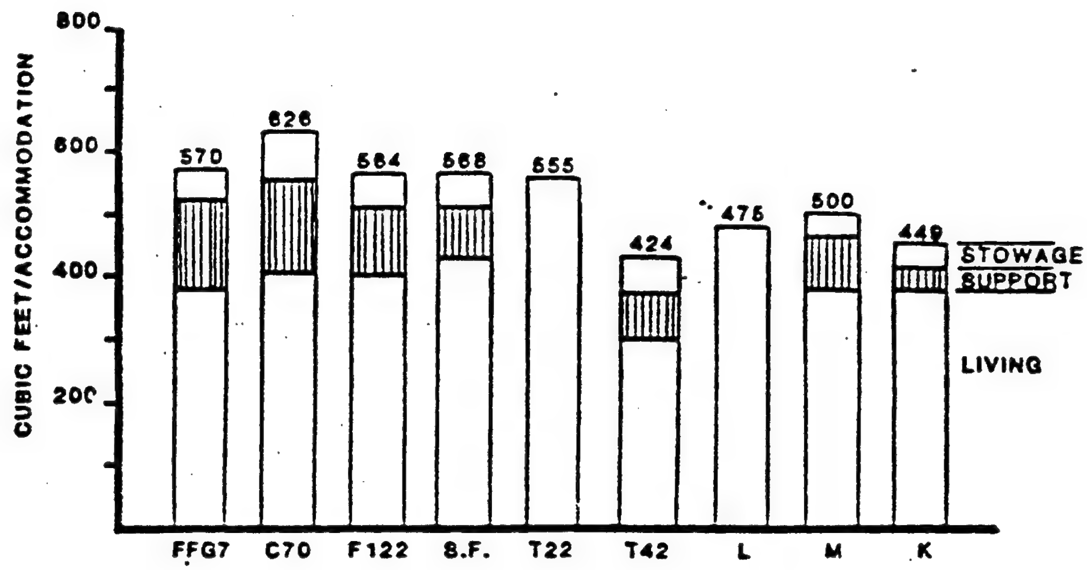
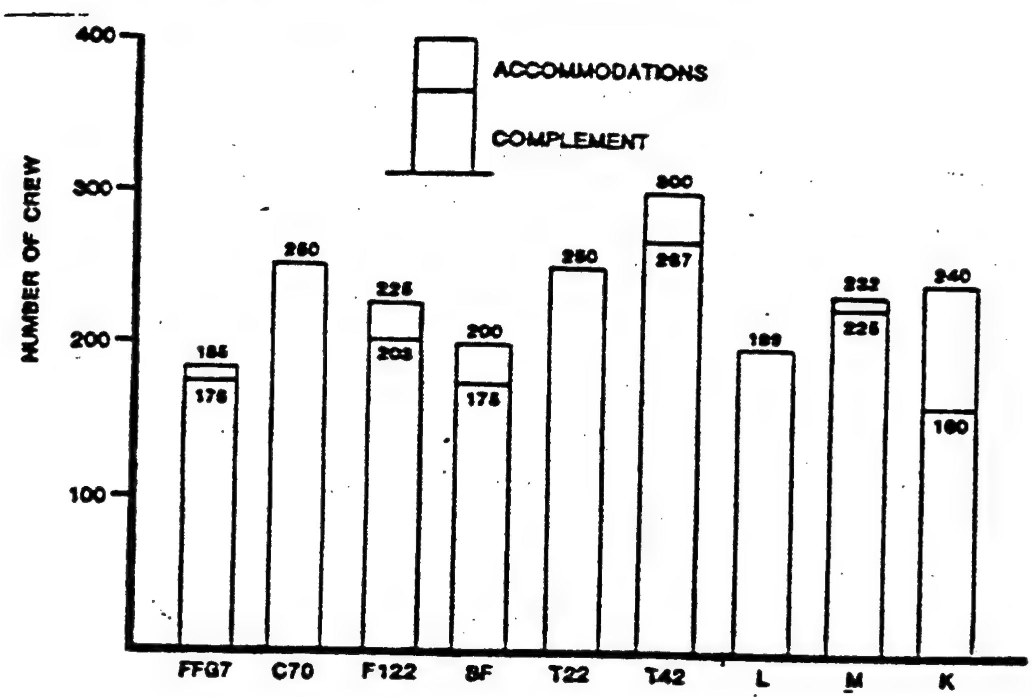
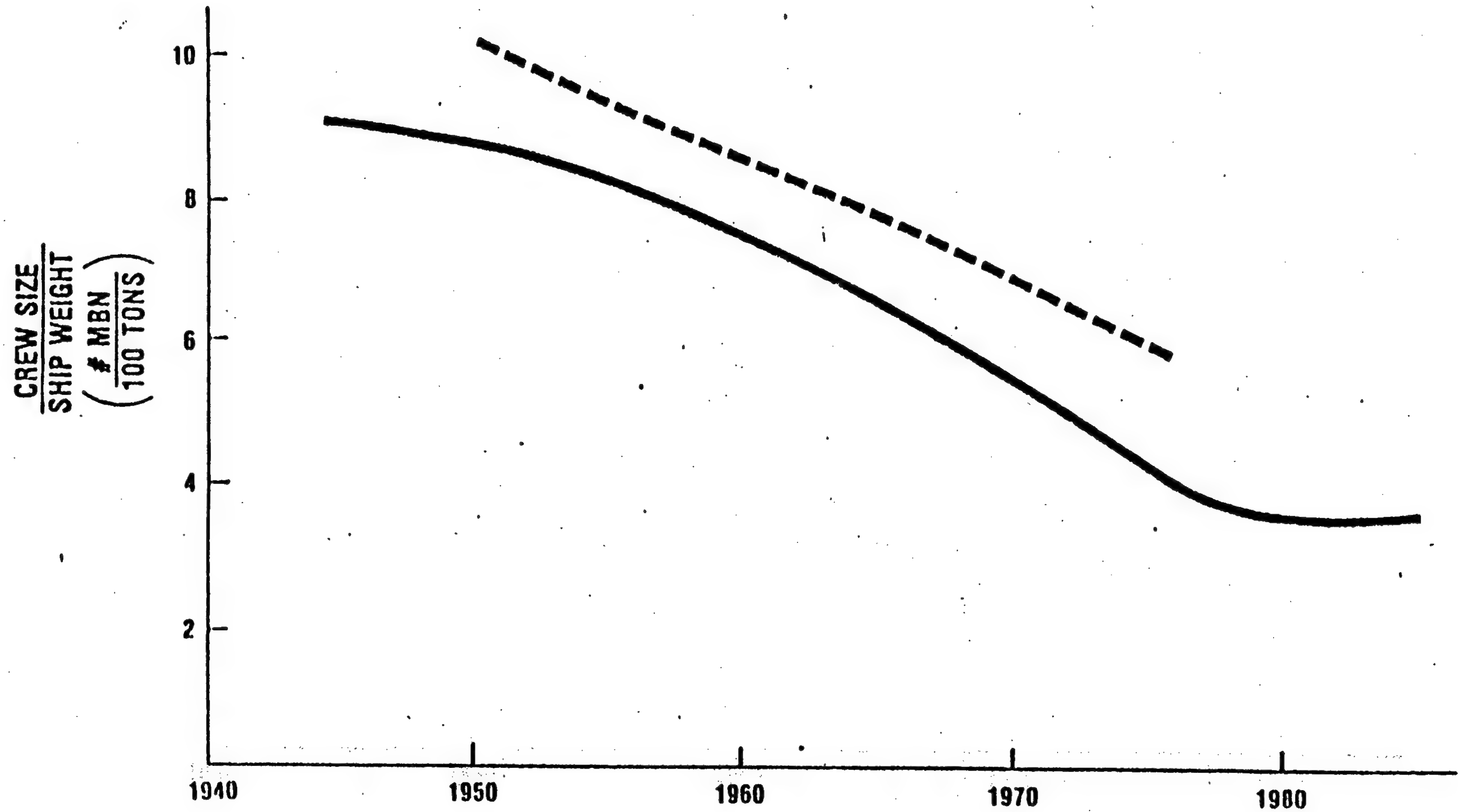


Fig 12 FRIGATES – CREW SIZE



10/11

Fig 13 CREW SIZE TREND



10 I

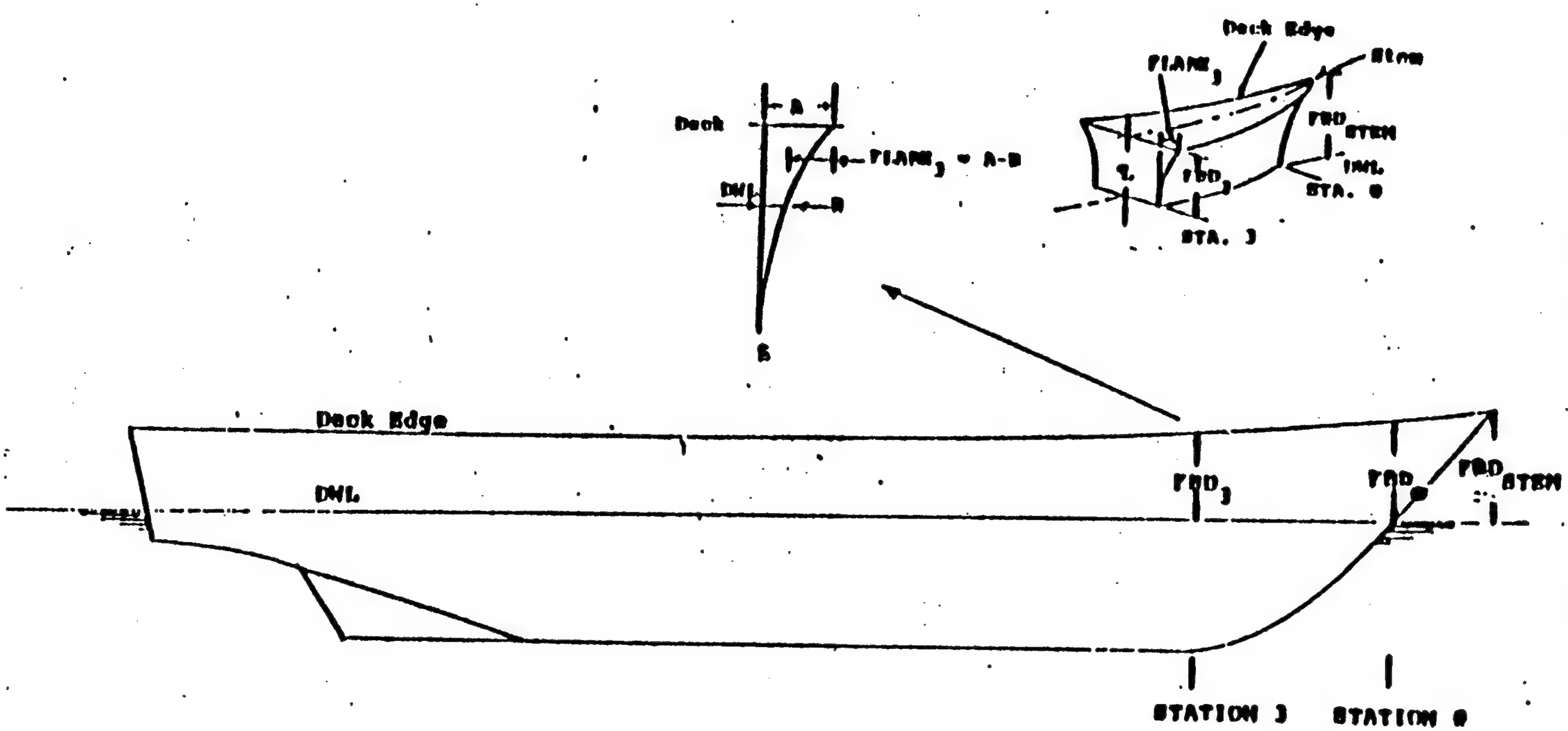


Fig 14 Freeboard and Flare Definitions

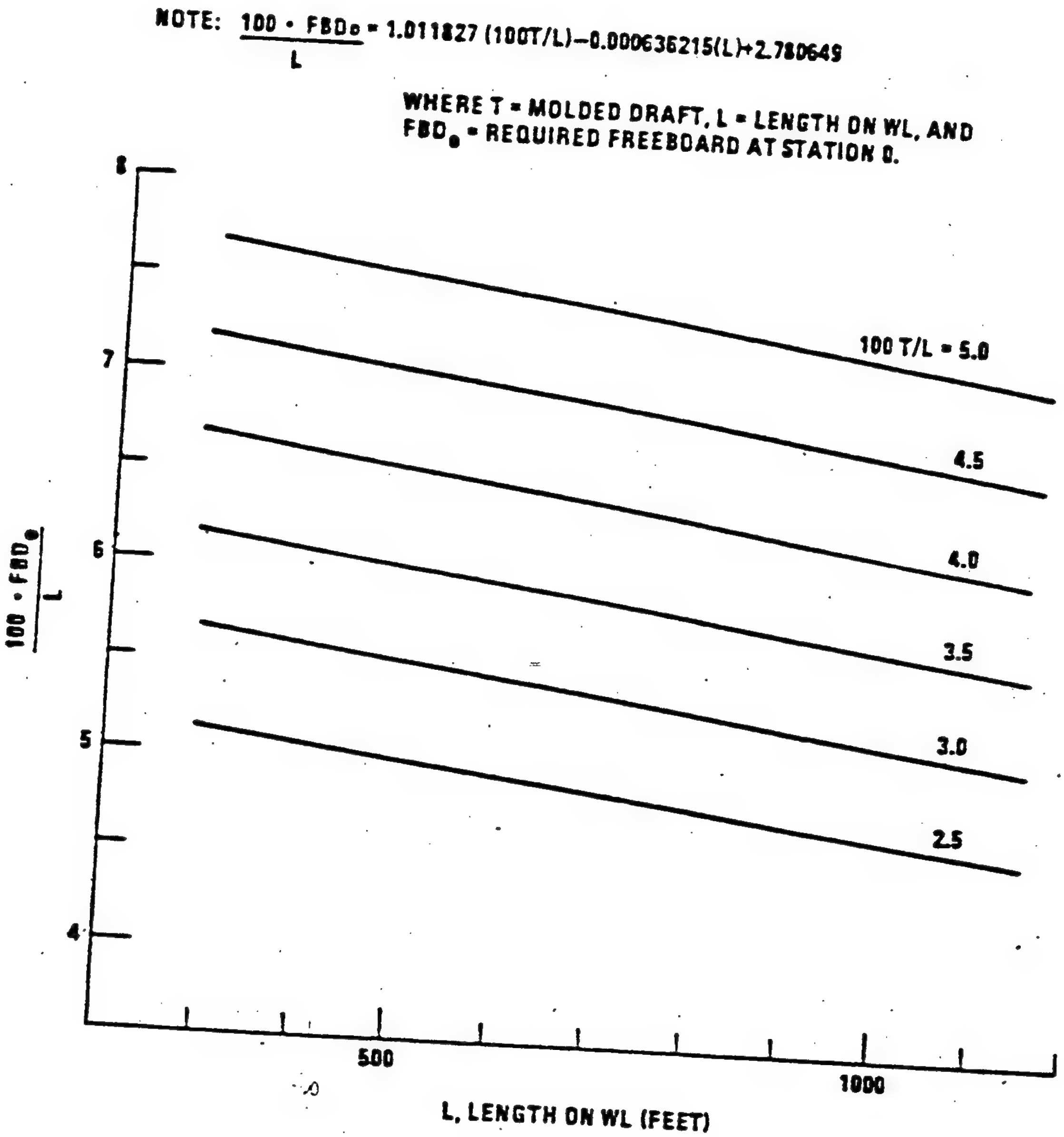


Fig 15 A Criterion for Bow Freeboard for Cruiser/Destroyer Ships

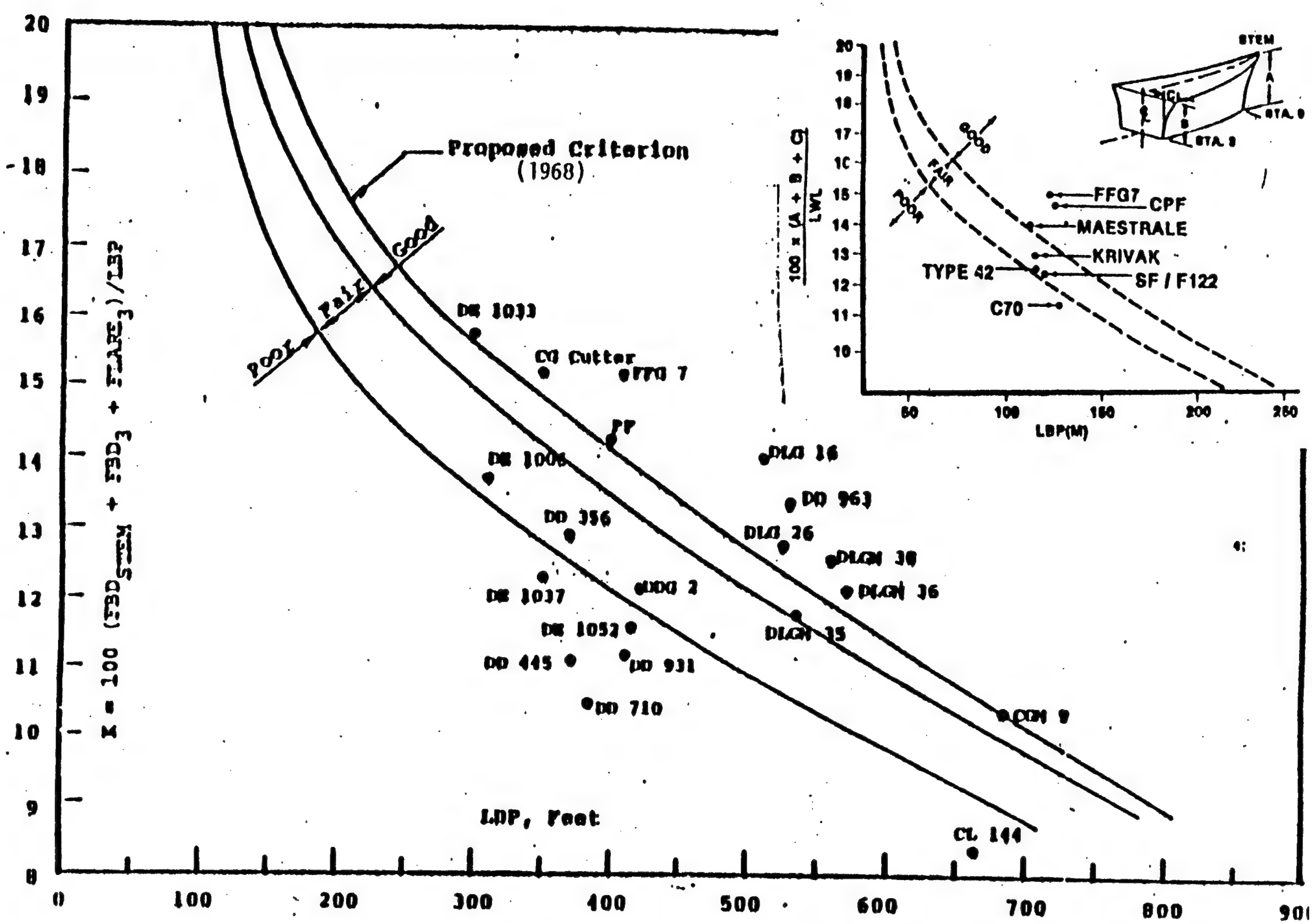


Fig 16 Combined Freeboard and Flare for Destroyer Type Ships.

SOURCE: DDS 079-2

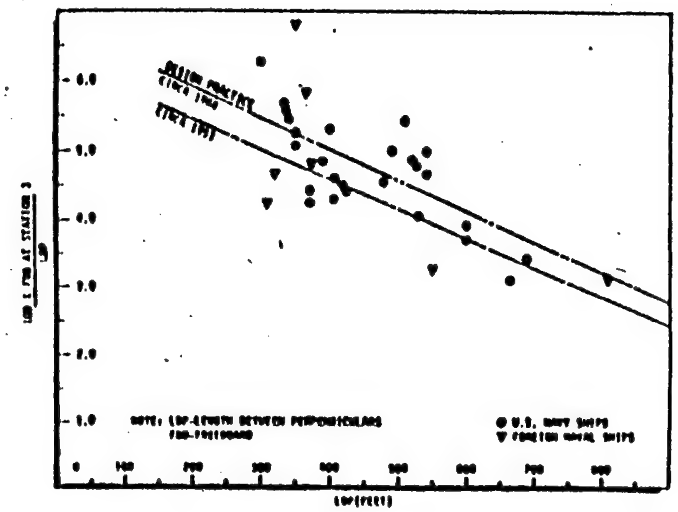


Figure 2. Freeboard Design Practice.

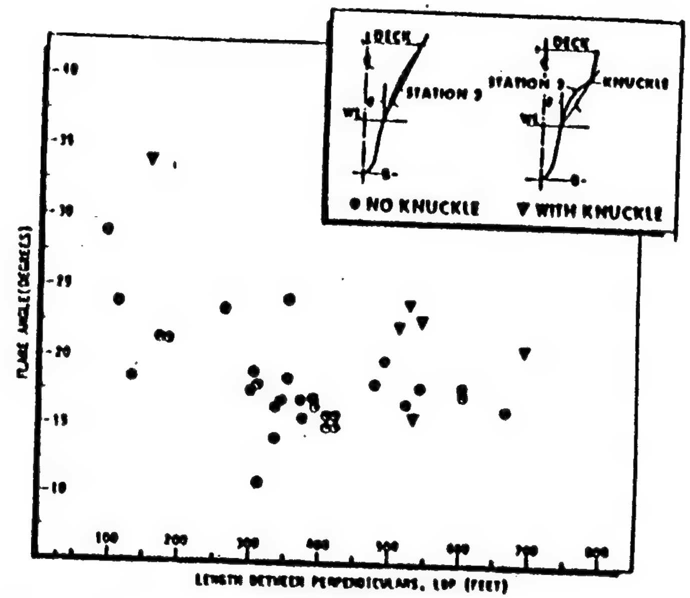


Figure 3. Correlation between FLARE and SHIP LENGTH.

SOURCE:

Fig 17 SEAKEEPING BY DESIGN COMSTOCK/KEANE Naval Engineers Journal, April 1980

10M

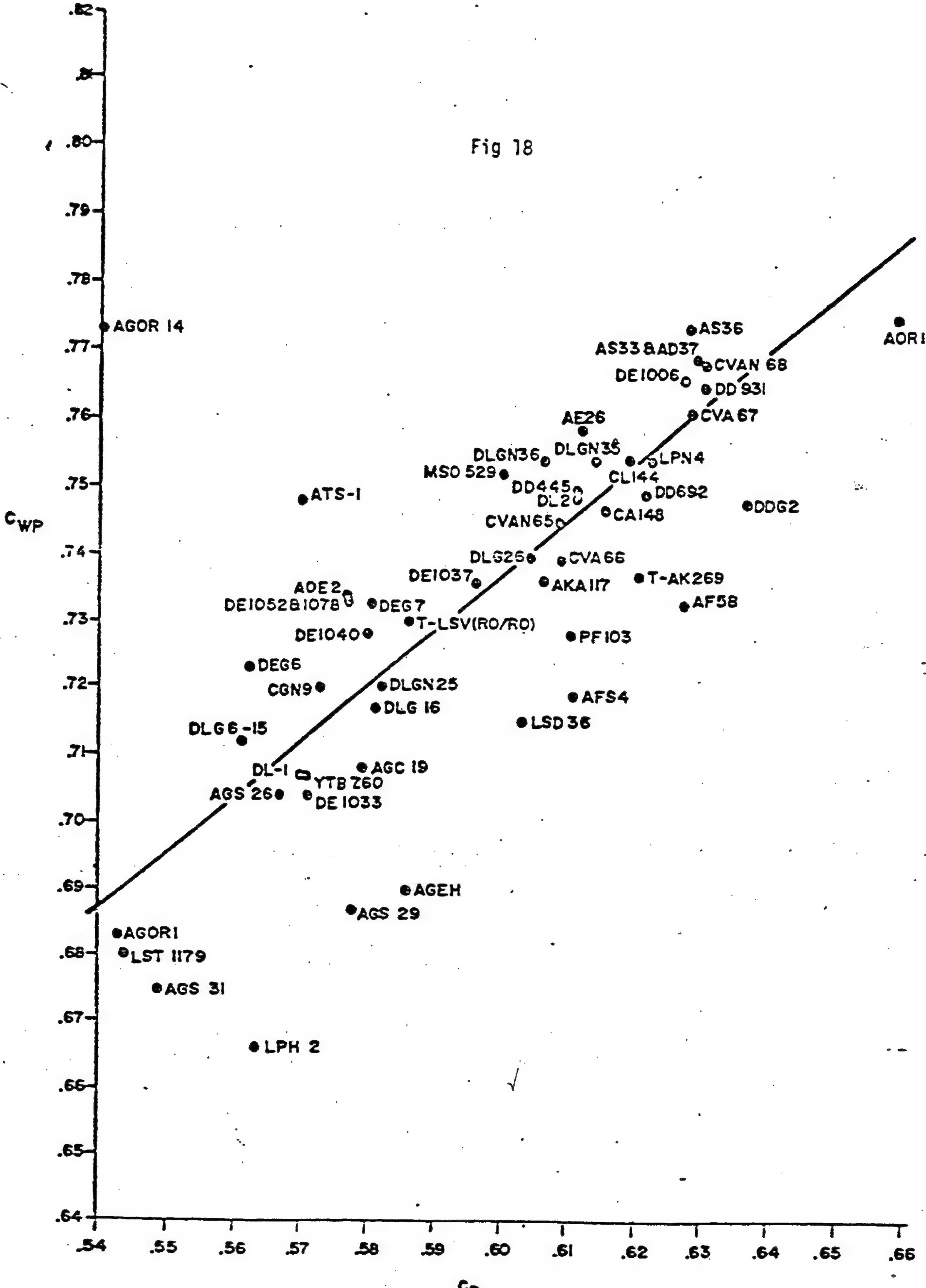


Fig 18
C_{WP}
C_P
.82
.81
.80
.79
.78
.77
.76
.75
.74
.73
.72
.71
.70
.69
.68
.67
.66
.65
.64
.54
.55
.56
.57
.58
.59
.60
.61
.62
.63
.64
.65
.66
AGOR 14
AS36
AS33 & AD37
CVAN 68
AOR 1
DE1006
DD 931
CVA 67
AE26
DLGN36
DLGN35
LPN4
MSO 529
CL144
DD445
DL2
DD692
ATS-1
DDG2
CA148
CVAN65
DLG26
CVA66
DE1037
T-AK269
AKA117
ADE2
DE1052 & 1078
DEG7
AF58
T-LSV(RO/RO)
DE1040
PF103
DEG6
CGN9
DLGN25
AFS4
DLG 16
LSD 36
DLG6-15
AGC 19
DL-1
YTB 760
AGS 26
DE 1033
AGEH
AGS 29
AGOR1
LST 1179
AGS 31
LPH 2

10 N

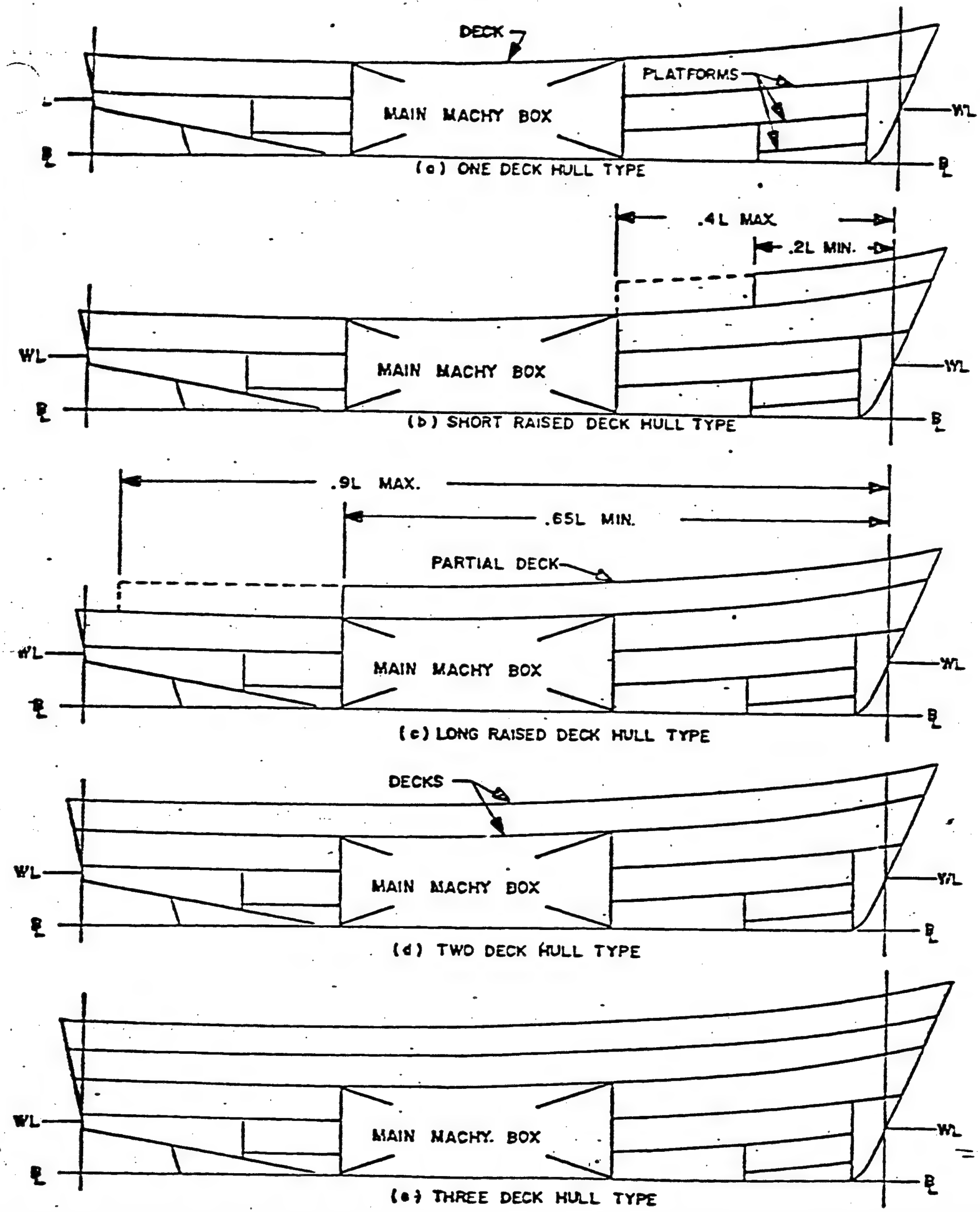

DECK
PLATFORMS
MAIN MACHY BOX
WL
(a) ONE DECK HULL TYPE
.4L MAX
.2L MIN.
WL
MAIN MACHY BOX
(b) SHORT RAISED DECK HULL TYPE
.9L MAX.
.65L MIN.
PARTIAL DECK
WL
MAIN MACHY BOX
(c) LONG RAISED DECK HULL TYPE
DECKS
WL
MAIN MACHY BOX
(d) TWO DECK HULL TYPE
WL
MAIN MACHY. BOX
(e) THREE DECK HULL TYPE

Fig 19

10 0

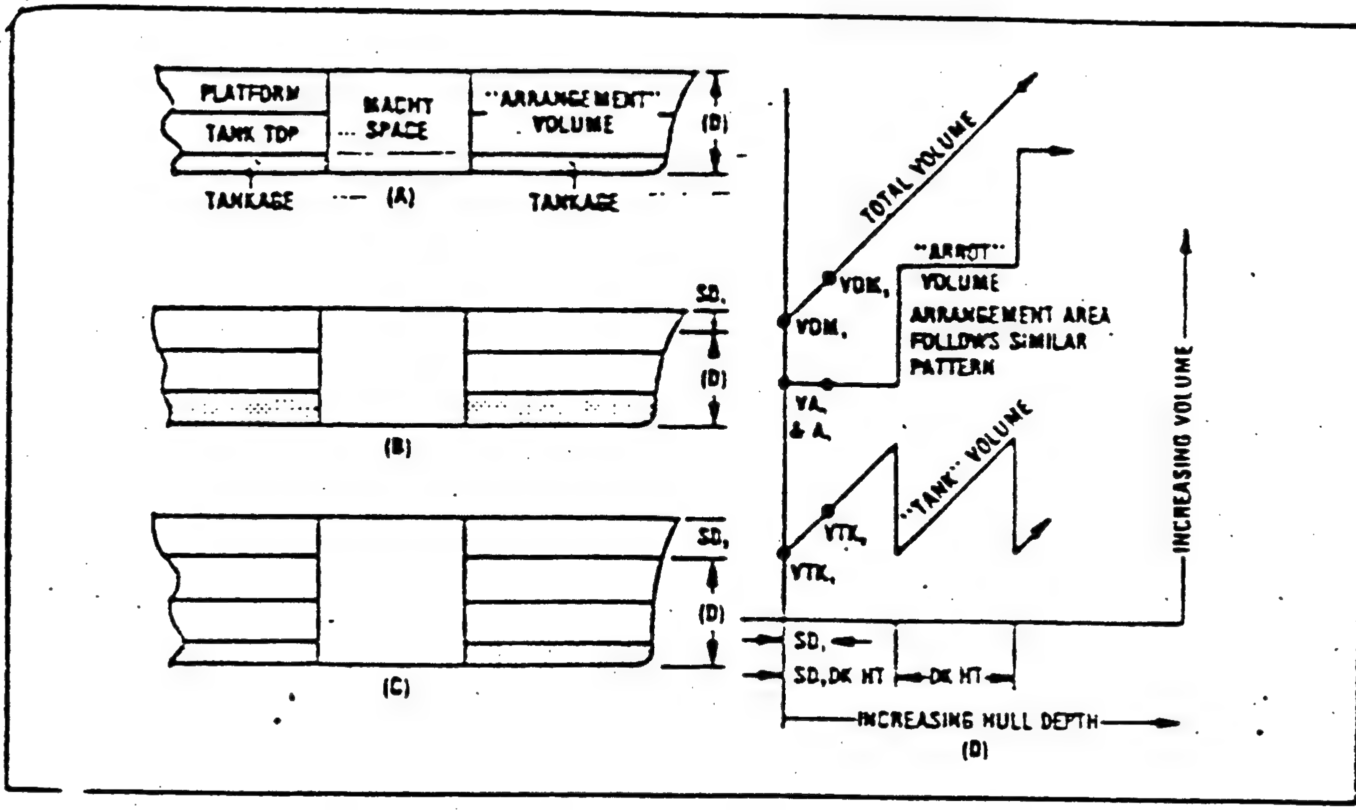


Figure 20 Idealized Area/Depth Relationship

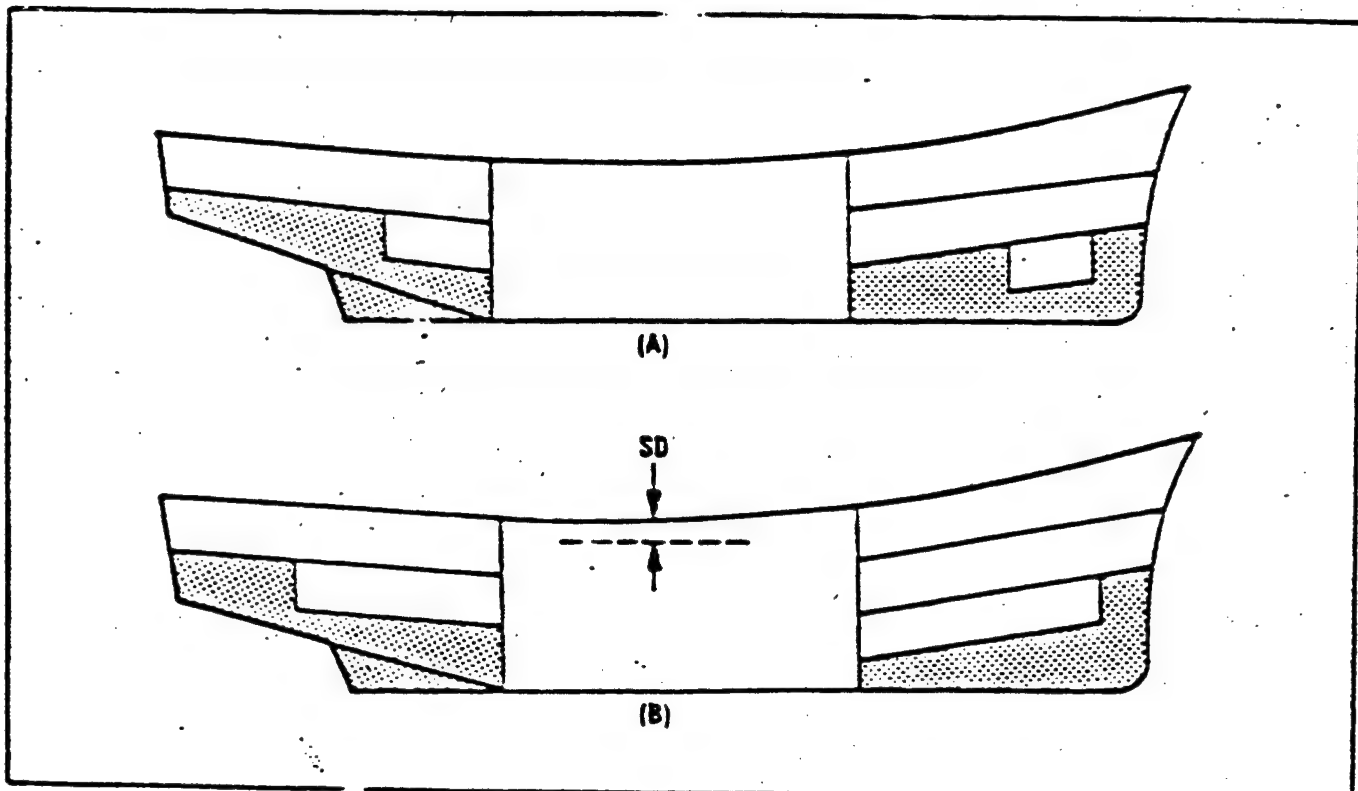


Figure 21 Typical Destroyer Profiles

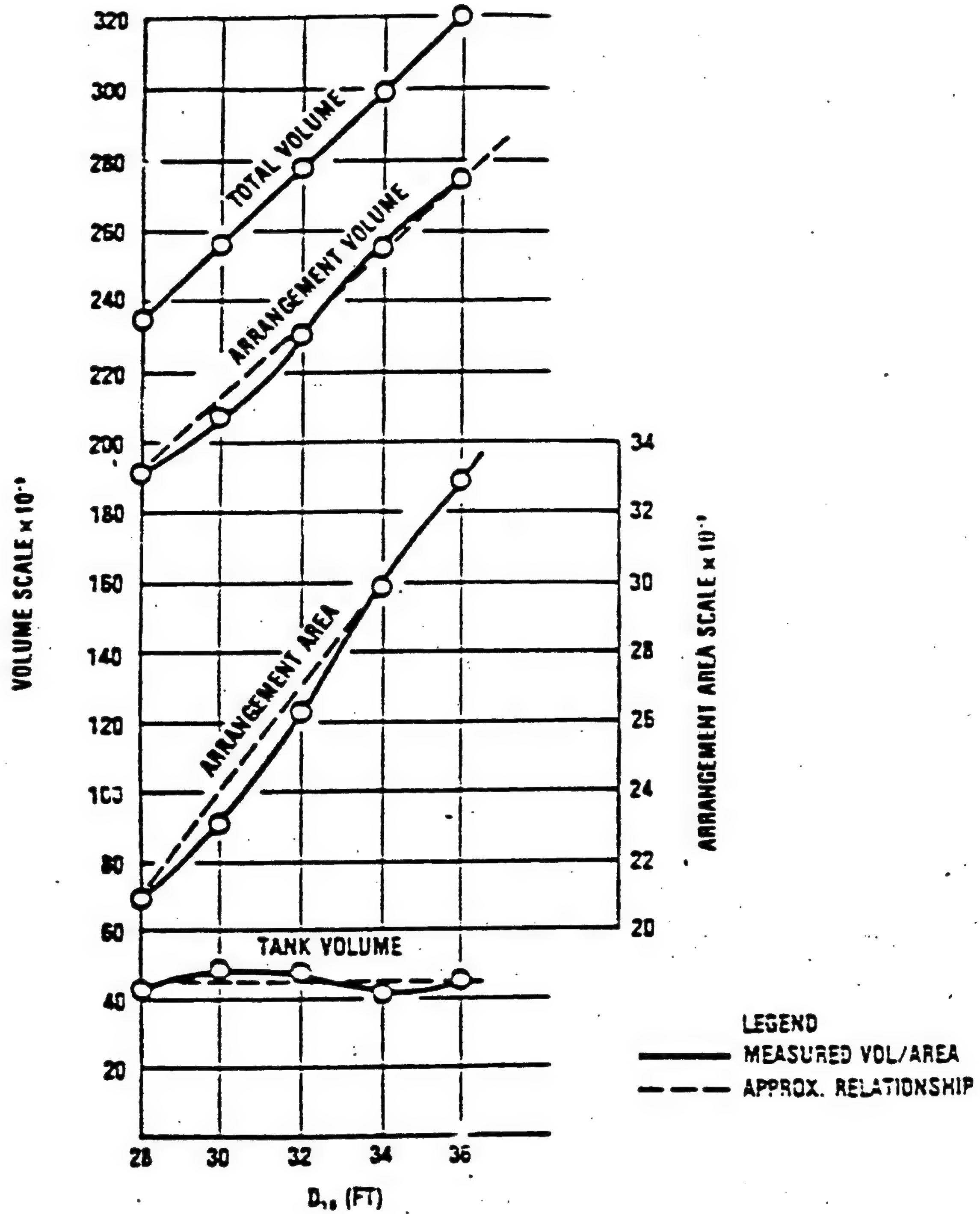
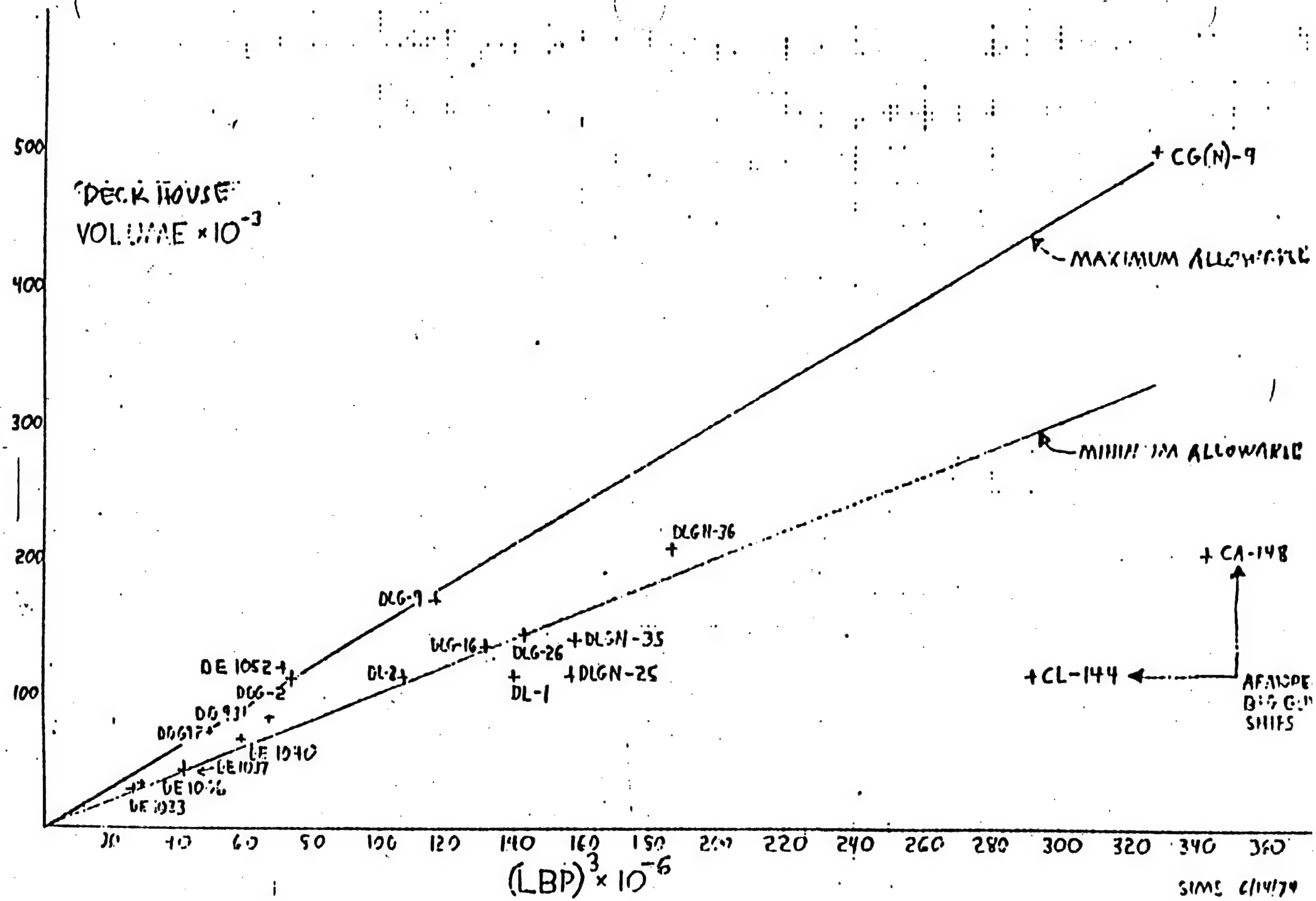


Figure 22 Area/Volume/Depth Relationships


DECK HOUSE
VOLUME × 10^-3
500
400
300
200
100
(LBP)^3 × 10^-6
40
60
80
100
120
140
160
220
240
260
280
300
320
340
360
+ CG(N)-9
MAXIMUM ALLOWABLE
ALLOWABLE
DLGN-36
+ CA-148
DLG-9
DLG-16
DLG-26
+ DLGN-35
+ DLGN-25
DL-1
DL-2
DE 1052
DDG-2
DDG 931
DE 1040
DE 1023
+ CL-144
SIMS

|Fig 23|

10R

Fig 24 FRIGATES – VOLUME

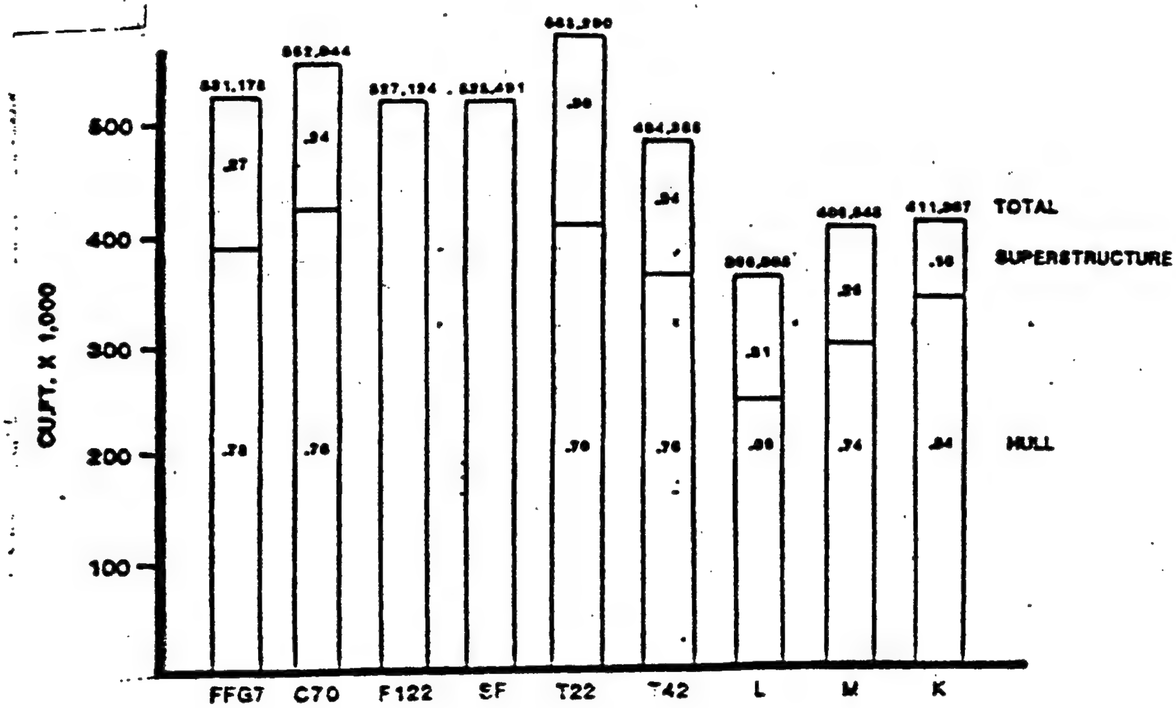
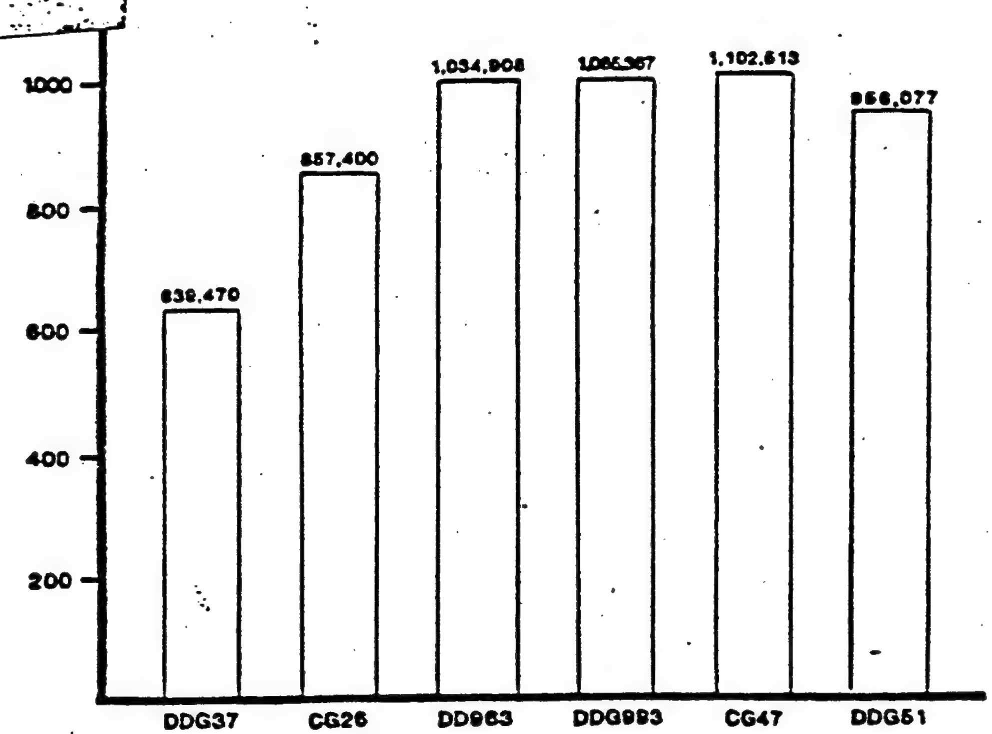


Fig 25 VOLUME – U.S. SHIPS



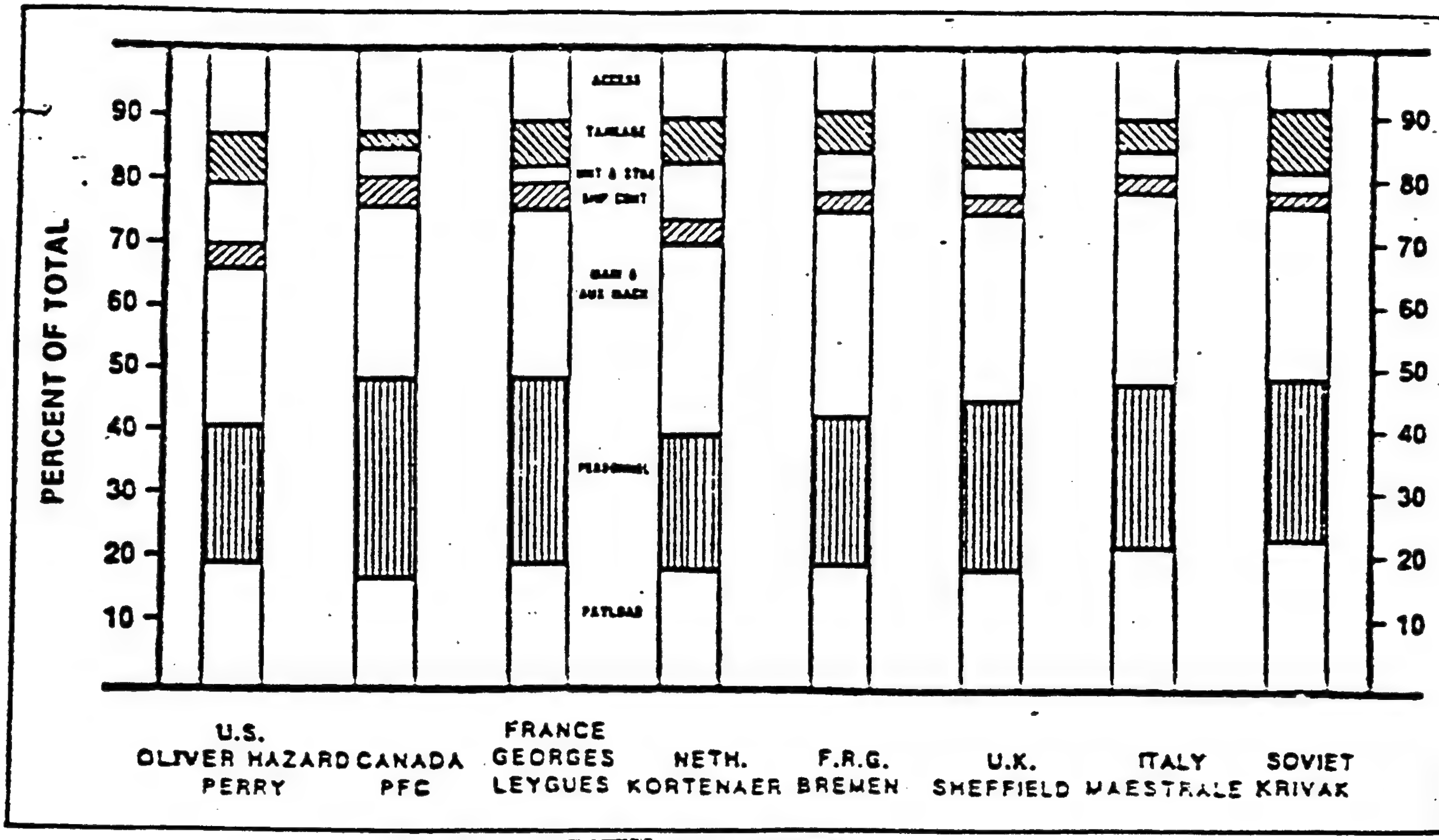
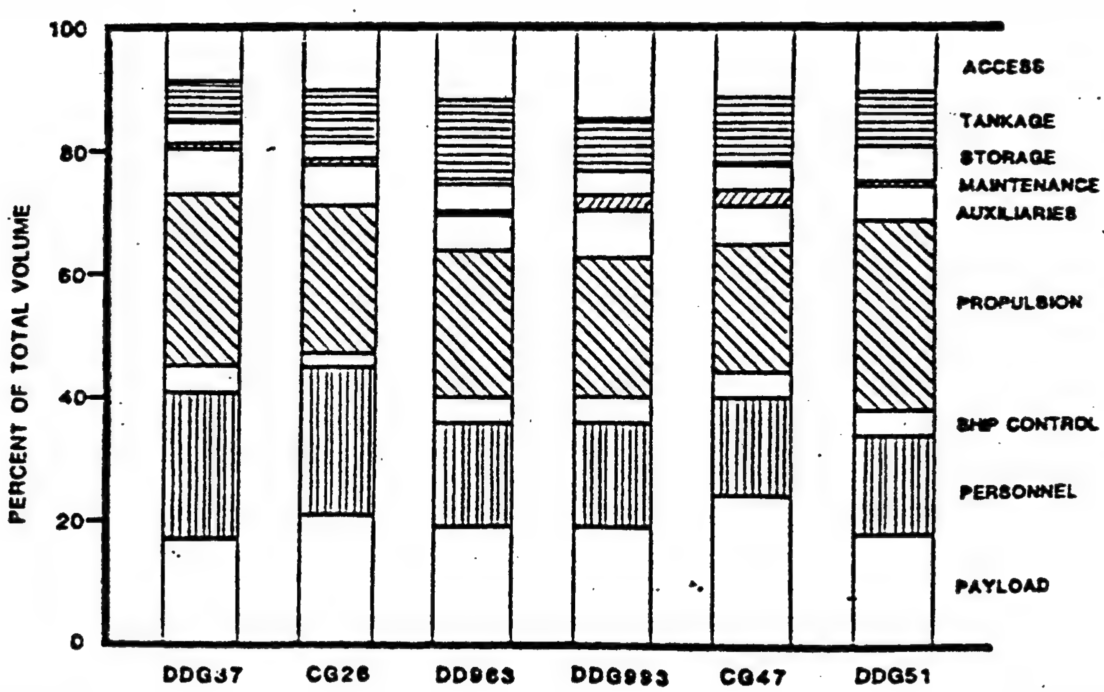


Fig 26 . Volume Distributions.

Fig 27 VOLUME DISTRIBUTION - U.S. SHIPS



10T

V. WEIGHT

Input : $L, B, T, P_I, N_S, \nabla_D, kW_B, \nabla_T, W_P, N_T, EP, CN, W_{MT}, W_{SD}$

$\downarrow$

V1.

P_I, L, D_P, N_S

$W_{BM} = f(P_I)$

$W_{ST} = f(L, D_P, N_S)$

$\downarrow$

Propulsion Machinery Weight

W_2

$\downarrow$

V2.

kW_B

$\downarrow$

Electrical Plant Weight

W_3

$\downarrow$

V3.

W_{PC}, CN

$\downarrow$

Communications/Control Weight

W_4

$\downarrow$

V4. and V5.

∇_T, N_T, B, D_{10}

$\downarrow$

Auxiliary Systems Weight

W_5

Outfit and Furnishing Weight

W_6

$\downarrow$

V6.

W_{PA}

$\downarrow$

Armament Weight

W_7

$\downarrow$

V7.

CN, ∇_D, W_{MT}, W_{SD}

W_{BH}, W_{DH}, W_{FD}

$\downarrow$

Hull Structure Weight

W_1

Light Ship Weight

W_L

$\downarrow$

V8.

Margin Policy

$\downarrow$

Margin Weight

W_g

$\downarrow$

V9. N_O, N_e , EP

W_C, W_{PRV}, W_{GSM}, W_W

W_F, W_{LO}, W_A

W_H, W_{HF}

$\downarrow$

Weight of Loads

W_{LD}

Total Ship Weight

W_T

$\downarrow$

Useful Output : All Weight Groups, ∇

V. WEIGHT ESTIMATING RELATIONSHIPS

V1. $W_{BM} = P_I \bullet (12.6 + 12.4 \bullet [P_I \bullet 10^{-5} - 1]^2)/2240$
$W_S = w_S \bullet L \bullet f_1$
where $w_S = 0.356$ tons/ft
$f_1 = 0.33$ for single screw ship
$W_B = 0.15 \bullet (W_S + W_{PR})$
$D_P = (0.6625 \bullet T + 0.0125 \bullet L) \bullet 1.2$
$W_{PR} = (0.05575\ [D_P]^{(5.497 - 0.0433\ D_P)}) \bullet N_S / 2240$
$W_{ST} = W_S + W_B + W_{PR}$
$W_2 = W_{BM} + W_{ST}$

V2. $kW_I = n \bullet kW_{GEN}$
where the following relationship must hold
$0.9 \bullet (n - 1) \bullet kW_{GEN} \geq 1.2 \bullet 1.2 \bullet kW_{max\ load}$
$kW_I \geq n \bullet kW_B / (n - 1)$
$W_3 = 50 + 0.03214 \bullet kW_I$

V3. W_{PC} = Input
$W_{CG} = 4.65$ CN
$W_{CO} = 2.24$ CN
$W_{CC} = 0.04\ (W_{PC} + W_{CG} + W_{CO})$
$W_4 = W_{PC} + W_{CG} + W_{CO} + W_{CC} + W_{SW}$

V4. $W_5 = 7.72 \times 10^{-8} \bullet \nabla_T^{1.443} + 5.14 \times 10^{-4} \bullet \nabla_T +$
$6.19 \times 10^{-4} \bullet \nabla_T^{.7224} + 0.0377\ N_T +$
$2.74 \times 10^{-4} \bullet P_I + 113.8 + W_{SS}$

V5. $W_{OFH} = 31.4 + 31.87 \times 10^{-5} \bullet \nabla_T$
$W_{OFP} = 0.504 \bullet (N_T - 95)$
$W_6 = W_{OFH} + W_{OFP}$

V6. $W_7 = W_{PA}$; Input

V7. $W_{BH} = 1.68341 \bullet CN^2 + 167.1721 \bullet CN - 23.283$
$W_{DH} = f_m \bullet \nabla_D$
where f_m = deck house material factor which
for steel is 1.429×10^{-3}
and for aluminum is 8.57×10^{-4}
$W_{FD} = 0.0675 \bullet W_{BM} + 0.072 \bullet (W_3 + W_4 + W_5 + W_7)$

W_{MT} = Input
W_{SD} = Input
$W_1 = W_{BH} + W_{DH} + W_{FD} + W_{MT} + W_{SD}$

$$W_L = \sum_{WG=1}^{7} W_{WG}$$

V8. $W_g = W_{margin} \bullet W_L$
V9. $W_C = (236 \bullet N_E + 400 \bullet [N_O + 1]) / 2240$
$W_{PRV} = N_T \bullet (2.8 \bullet EP_{DRY} + 2.2 \bullet EP_{CHL} + 1.3 \bullet EP_{FRZ} + 1.3 \bullet EP_{GSM} + 22.6) / 2240$
$W_{GSM} = 9.598 \times 10^{-4} \bullet N_T \bullet EP_{GSM}$
$W_W = 0.224 \bullet N_T$
W_A, W_H, W_{HF}, W_{LO} all input values
$W_{LD} = W_C + W_{PRV} + W_{GSM} + W_W + W_A + W_H + W_{HF} + W_F + W_{LO}$
$W_T = W_L + W_{LD} + W_g$

Fig 1 STRUCTURES – HULL GIRDER WEIGHT

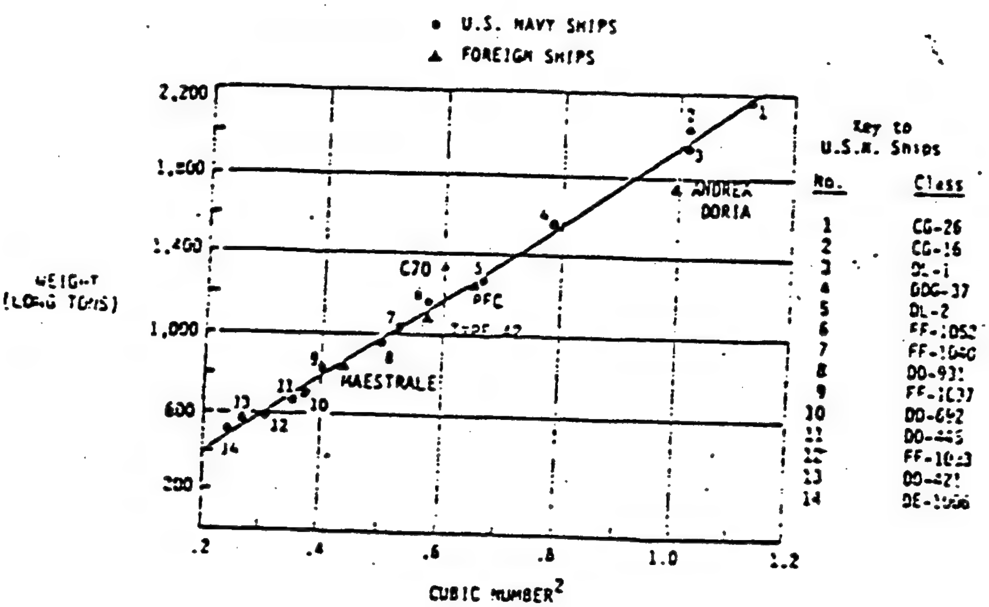
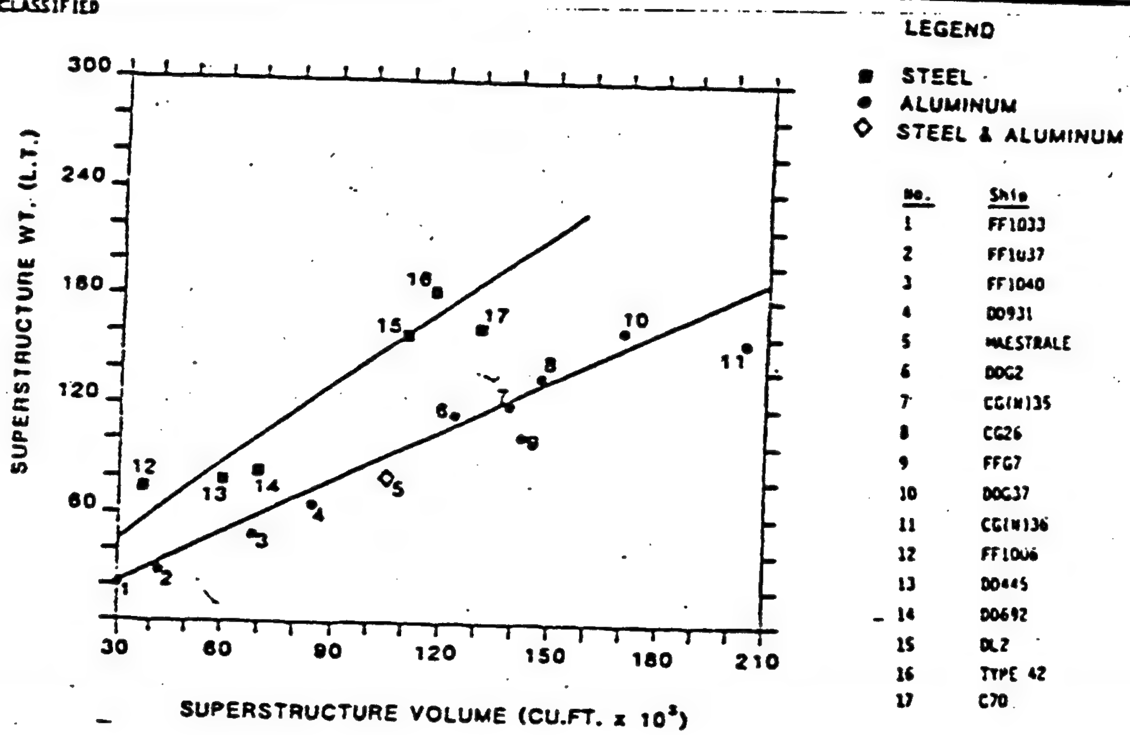


Fig 2 SUPERSTRUCTURE WEIGHT

UNCLASSIFIED



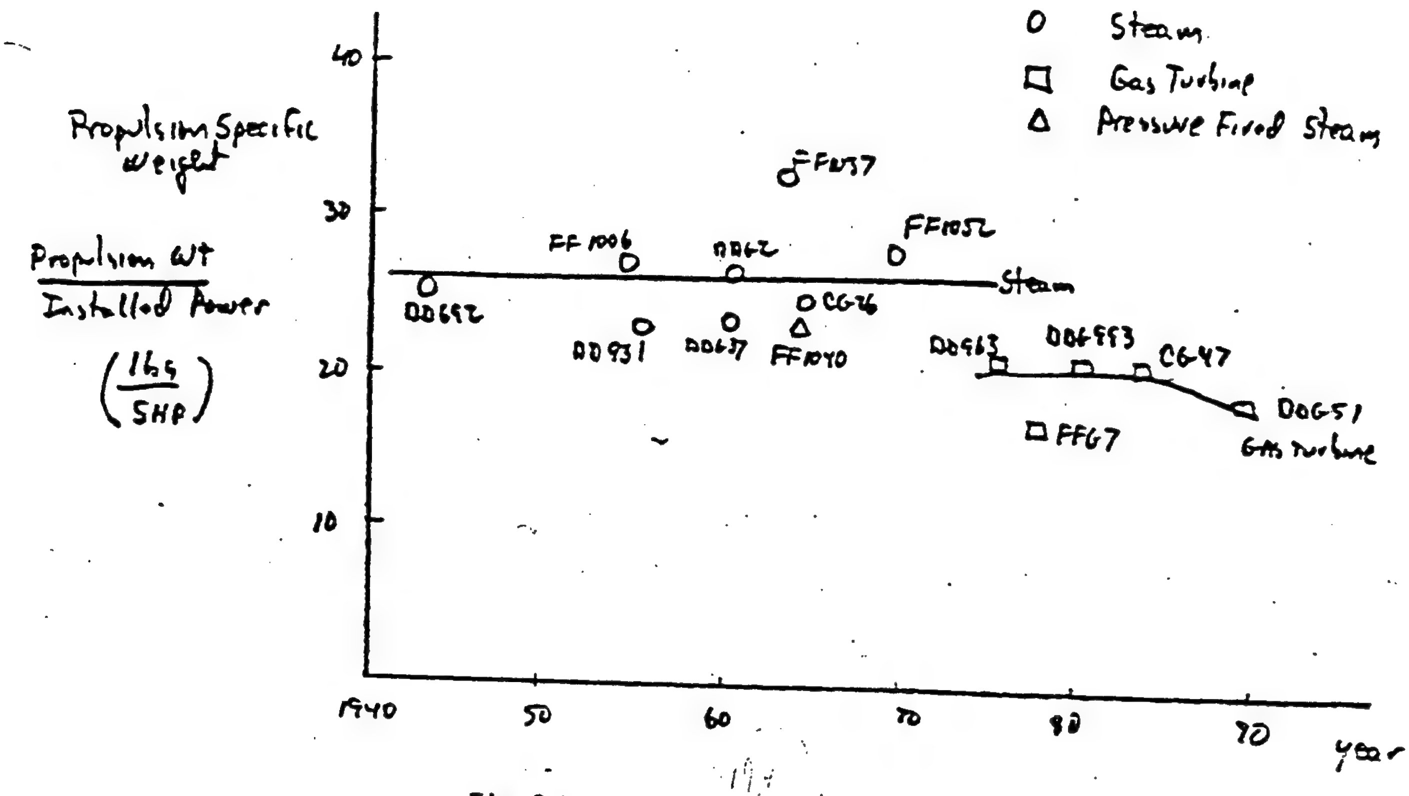


Fig 3

Fig 4 **FRIGATES – PROPULSION WEIGHT**

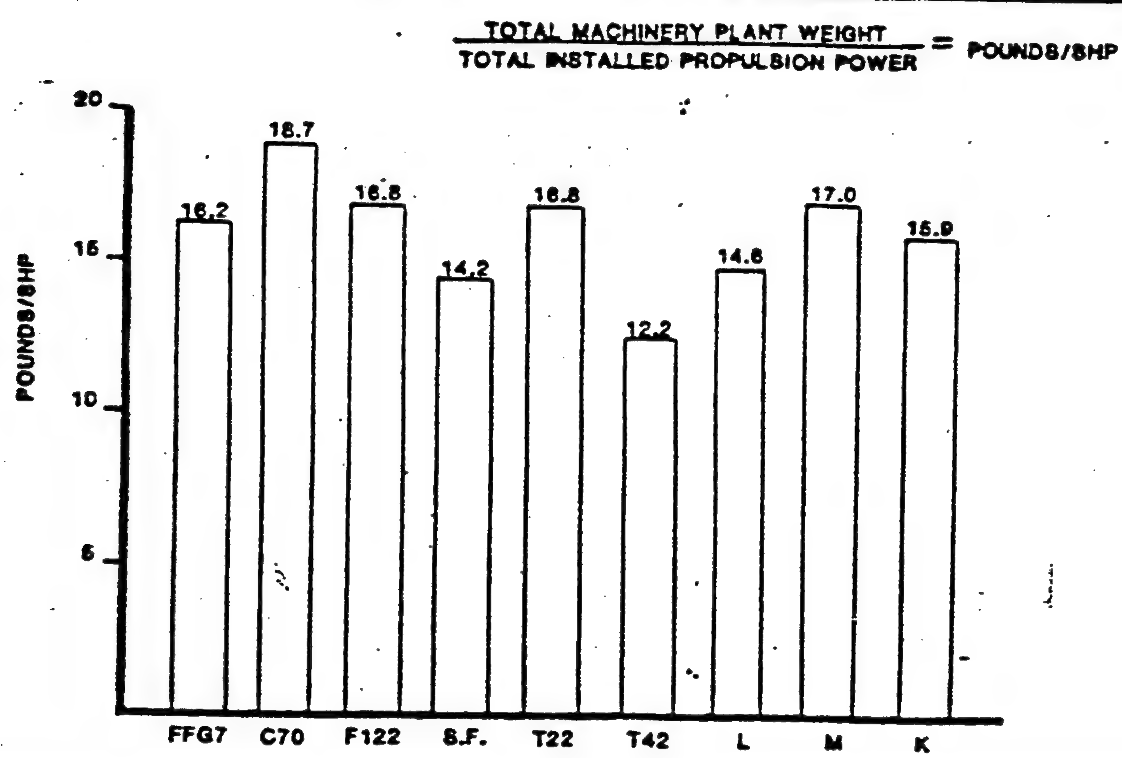


Fig 5 FRIGATES – PAYLOAD WEIGHT DISTRIBUTION

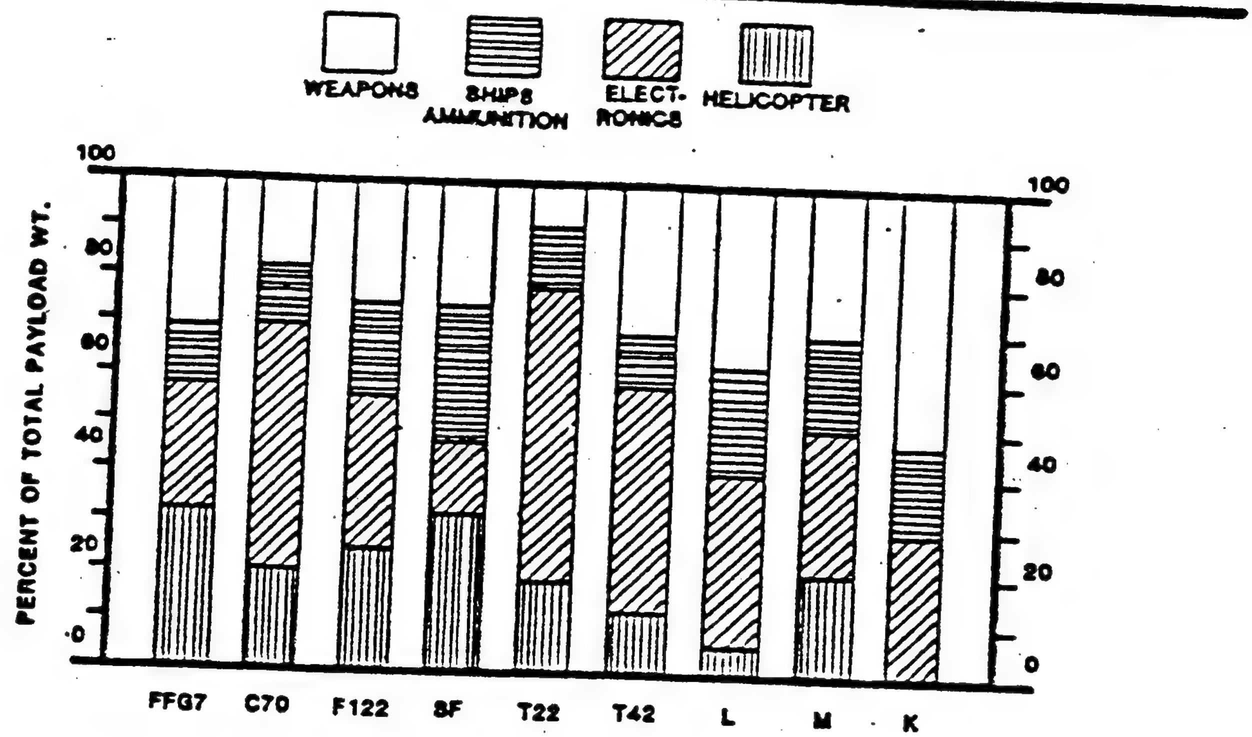
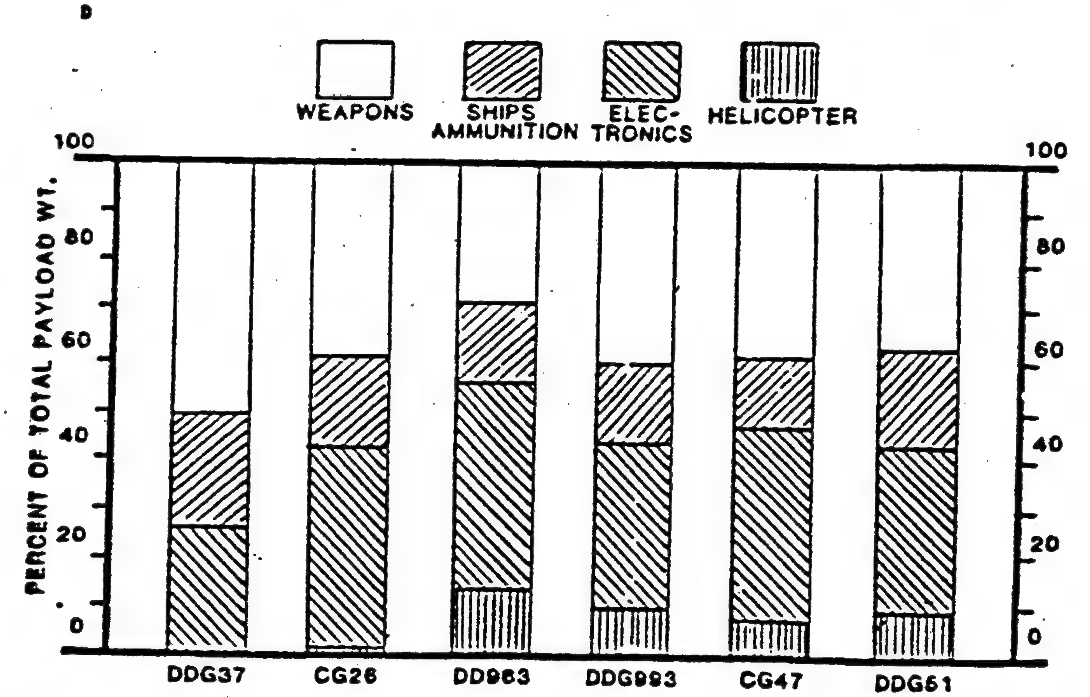


Fig 6 PAYLOAD WEIGHT DISTRIBUTION – U.S. SHIPS



$\frac{W}{W_{cs}}$

14C

Fig 7 FRIGATE - SPECIFIC PAYLOAD VOLUME (U)

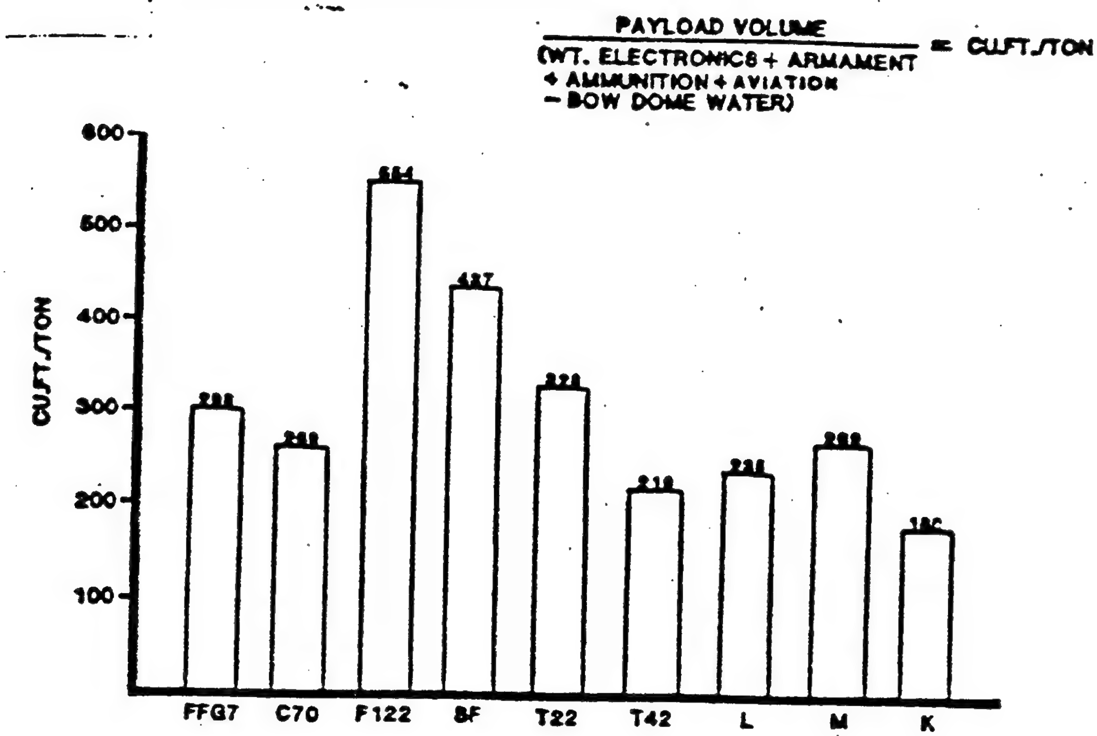
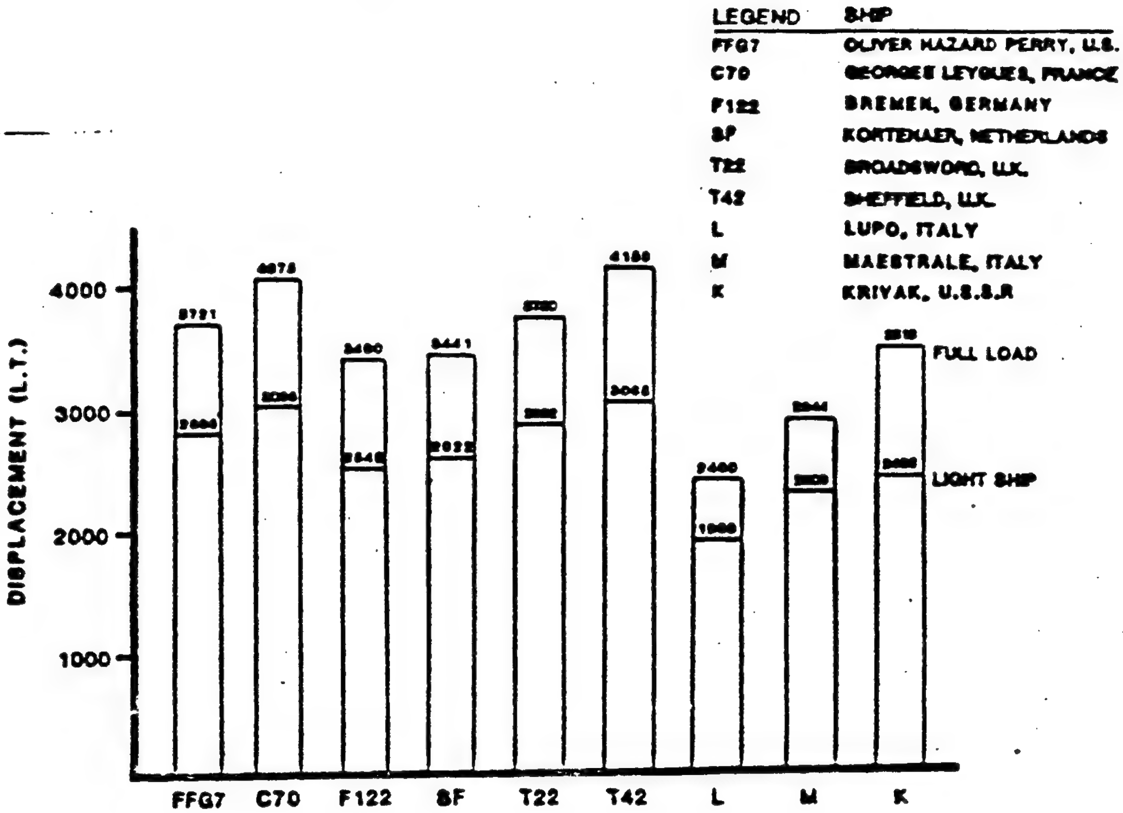


Fig 8 FRIGATES - DISPLACEMENT



4-21

Fig 9 LIGHT SHIP WEIGHT DISTRIBUTION - FRIGATES

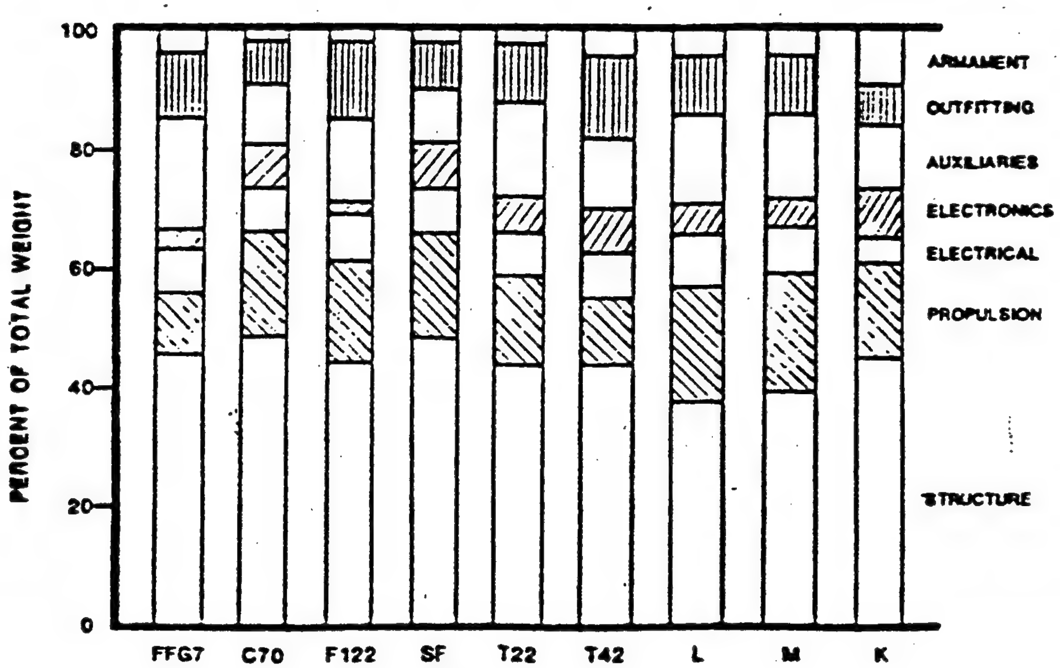


Fig 10 WEIGHT — U.S. SHIPS

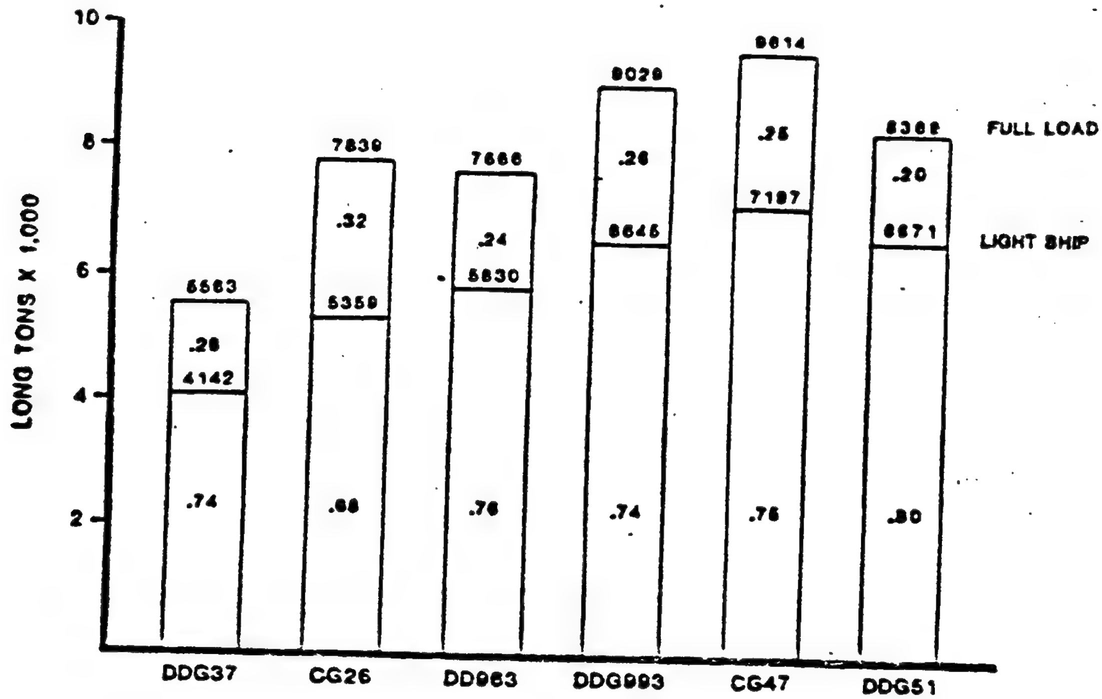
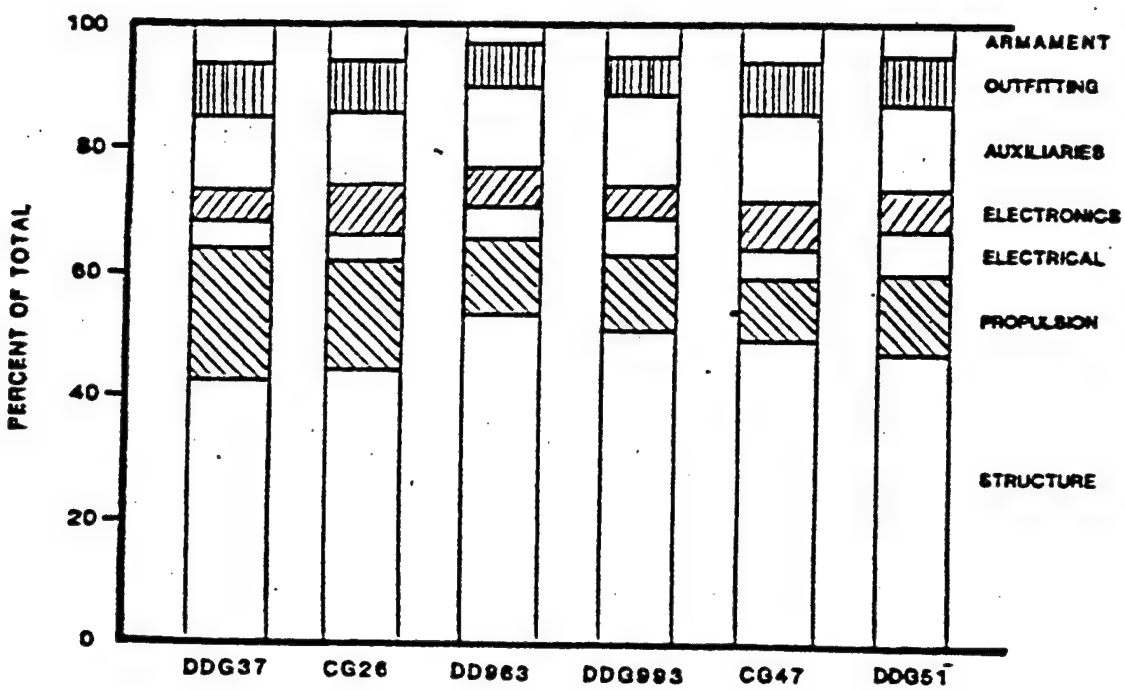


Fig 11 LIGHT SHIP WEIGHT DISTRIBUTION
— U.S. SHIPS



14F

VI. STABILITY

Input : D_{AV}, ∇_T, ∇_D, L, D_{10}, T, H_{MB}, B, Weight Groups

VI1.

Inputs

↓

VCGs of Weight Groups
VCGs of Loads

↓

VI2.

Moment of Weight Groups
Weight of Weight groups
W_{margin}
KG_{margin}

↓

W_g
KG_{Lnm}
KG_L

↓

VI3.

Moment of Loads
Weight of Loads
C_P, ∇_T, B, L

↓

KG
C_W
KB
BM
GM

Useful Output: GM / B

VI. STABILITY ESTIMATING RELATIONSHIPS

Input Calculations : **<u>(all VCGs in feet above baseline)</u>**

SWBS	WEIGHT VARIABLE	VCG FORMULA
1	W_{BH}	$VCG_{BH} = 0.527 \bullet D_{AV}$
1	W_{DH}	$VCG_{DH} = D_{10} + 2.45 \bullet \nabla_D / (L \bullet B)$
1	W_{FD}	$VCG_{FD} = 0.68 \bullet D_{10}$
1	W_{MT}	$VCG_{MT} = 2.65 \bullet D_{10}$
1	W_{SD}	$VCG_{SD} = -2.5$
2	W_{BM}	$VCG_{BM} = 0.55 \bullet D_{10}$
2	W_{ST}	$VCG_{ST} = 3.9 + 0.19 \bullet T$
3	W_3	$VCG_3 = 0.7 \bullet D_{10}$
4	W_{SW}	$VCG_{SW} = -2.5$
4	W_{PC}	VCG_{PC} = Input (Note: use D_{AV} to bring to BL)
4	W_{CG}	$VCG_{CG} = D_{10}$
4	W_{CO}	$VCG_{CO} = 5.6 + 0.4625 \bullet D_{10}$
4	W_{CC}	$VCG_{CC} = 16$
5	W_{BA}	$VCG_{BA} = 1.1 \bullet (D_{10} - 7.4)$
5	W_{SS}	$VCG_{SS} = 0.5 \bullet H_{MB}$
6	W_{OFH}	$VCG_{OFH} = 0.805 \bullet D_{10}$
6	W_{OFP}	$VCG_{OFP} = 8 + 0.71 \bullet D_{10}$
7	W_7	VCG_7 = Input (Note: use D_{AV} to bring to BL)
L	W_C	$VCG_C = 0.746 \bullet D_{10}$
L	W_{PRV}	$VCG_{PRV} = 10$

L	W_{GSM}	$VCG_{GSM} = 20$
L	W_W	$VCG_W = 7.5$
L	W_A	VCG_A = Input (Note: use D_{AV} to bring to BL)
L	W_{LO}	$VCG_{LO} = 0.728 \bullet D_{10}$
L	W_F	$VCG_F = 7.5$
L	W_{HF}	$VCG_{HF} = 7.5$
L	W_g	VCG_g = VCG light ship = M_L / W_L
L	W_H	VCG_H = Input (Note: use D_{20} to bring to BL)

VI1. $M_{WG} = W_{WG} \bullet VCG_{WG}$

VI2. $M_L = \sum M_{WG}$
$W_L = \sum W_{WG}$
VCG_g = VCG light ship = M_L / W_L
$KG_{Lnm} = VCG_g$
$KG_L = KG_{Lnm} \bullet (1 + KG_{margin})$

VI3. $M_{LD} = \sum M_{\text{individual loads}}$
$KG_{LD} = M_{LD} / W_{LD}$
$M_T = W_{LD} \bullet KG_{LD} + KG_L \bullet (W_L + W_g)$
$KG = M_T / W_T$
$C_W = 0.236 + 0.836 \bullet C_P$
$C_m = C_x$
$KB = (T/3) \bullet (2.5 - C_P \bullet C_m / C_W)$, Morrish's Formula
$C_{IT} = -.497 + 1.44 \bullet C_W$
$BM = (L \bullet B^3 \bullet C_{IT}) / (12 \bullet \nabla_{HV})$
$GM = KB + BM - KG$

Final Check : GM/B must be within design range.

TAYLOR STANDARD SERIES
MADE EASY

PURPOSE

GIVEN SHIP PARAMETERS, PREDICT
EFFECTIVE HOUSEPOWER USING
TAYLOR STANDARD SERIES

REFERENCE

DESIGN DATA SHEET 051-1 OF 15 MAY 1984

THIS DDS USES A REANALYSIS OF TAYLOR'S
ORIGINAL DATA BY GERTLER, AND ADDS MANY FACETS
OF ACTUALLY PERFORMING A POWERING CALCULATION.

METHOD

USE THE ATTACHED TABLE TO STEP
THROUGH THE CALCULATIONS

CODE	VARIABLE	FORMULA or EXPLANATION of VARIABLE	VALUE
1	L	Length on Waterline (LBP)	
2	B_X	Beam at maximum section on design waterline	
3	T_X	Draft to design waterline at maximum section	
4	Δ_{FL}	Total displacement at draft T_X	
5	Δ_{APP}	Displacement of appendages	0
6	Δ_{BH}	Bare hull displacement (without appendages)	
7	C_X	Maximum section coefficients	
8	C_P	Prismatic Coefficient	
9	B_X/T_X	Beam to Draft ratio	
10	∇_{BH}	Bare hull displacement volume $\{6\}\bullet\{35\}$	
11	C_V	Bare hull volumetric coefficient $\{10\}/\{1\}^3$	
12	D_P	Propeller diameter, $(0.6625\bullet\{3\} + 0.0125\bullet\{1\})\bullet 1.2$	
13		Number, type of Propellers	
14	A_V	Frontal area of the ship to predict wind resistance	
15	T_{SW}	Temperature of seawater	59 °F
16	ρ_{SW}	Density of seawater at given temperature	1.9905 $lbf\bullet sec^2/ft^4$
17	ν_{SW}	Kinematic viscosity of seawater at given temperature	1.2817×10^{-5} ft^2/sec
18	C_A	Correlation Allowance	0.0005
19	$\frac{C_{S(SHIP)}}{C_{S(TSS)}}$	Ratio of wetted surface coefficients	1.0
20	$C_{S\,(TSS)}$	Wetted surface coefficient of TSS, Use figure 1 with C_P and B/T	
21	$C_{s(ship)}$	Wetted Surface coefficent of ship (if known)	unknown

CODE	VARIABLE	FORMULA or EXPLANATION of VARIABLE	VALUE
22	$CD_{(APP)}$	Drag coefficient of appendages. Use figure 2 or 3 with L	
23	C_{AA}	Air drag coefficient	0.0
24	PMF	Power Margin factor - Depends on design stage, usually 10% in early stages	1.10
25	$S_{(TSS)}$	Wetted Surface (SHIP), $\{20\}\bullet\{10\}^{0.5}\bullet\{1\}^{0.5}$	
26	$S_{(SHIP)}$	Wetted Surface (SHIP) $\{25\}\bullet\{19\}$	
a	V	Ship speed (knots), (endurance, threshold, and goal)	1. 2. 3.
b	$V/\sqrt{L}$	Speed to length ratio, $\{a\} / \{1\}^{0.5}$	1. 2. 3.
c and 27	R_N	Reynold's Number $1.689\bullet\{1\}\bullet\{a\}/\{17\}$	1. 2. 3.
d and 28	C_F	Frictional resistance Coefficient $0.075/\{[\log_{10}(\{27\}) - 2]^2\}$	1. 2. 3.
e and 29	R_F	Frictional Resistance, $1.4264\bullet\{16\}\bullet\{26\}\bullet\{a\}^2\bullet[\{18\}+\{28\}]$	1. 2. 3.
f	$C_{R\,2.25}$	Use Taylor Standard Series with $\{8\}$, $\{11\}$ and $\{b\}$ @ B/T = 2.25	1. 2. 3.
g	$C_{R\,3.00}$	Use Taylor Standard Series with $\{8\}$, $\{11\}$ and $\{b\}$ @ B/T = 3.00	1. 2. 3.

CODE	VARIABLE	FORMULA or EXPLANATION of VARIABLE	VALUE
h	$C_{R\,3.75}$	Use Taylor Standard Series with *{8}* , *{11}* and *{b}* @ B/T = 3.75	1. 2. 3.
31		Form Factor $\frac{4}{3}\cdot[\frac{Bx}{Tx}-3]$	
i		(*{h}*-*{f}*) /2	1. 2. 3.
j		[(*{f}* + *{h}*)/2] - *{g}*	1. 2. 3.
k		*{31}*•*{i}*	1. 2. 3.
l		$\{31\}^2\bullet\{j\}$	1. 2. 3.
m and 30	$C_{R(TSS)}$	Residuary resistance Coefficient, $\{g\}+\{k\}+(\{31\}^2 \times \{j\})$	1. 2. 3.
n and 32	$R_{R(TSS)}$	Residuary Resistance (TSS), $1.4264 \times (\{16\}\bullet\{25\}\bullet\{m\}\bullet\{a\}^2)$	1. 2. 3.
o	WCF	Worm Curve Factor, use figures 4 through 9 with *{b}*	1. 2. 3.
p	R_R	Residuary resistance (ship), *{n}* • *{o}*	1. 2. 3.

CODE	VARIABLE	FORMULA or EXPLANATION of VARIABLE	VALUE
q	R_T	Total Resistance, $\{e\} + \{p\}$	1. 2. 3.
r	P_E	Effective Horsepower, $\{a\} \bullet \{q\} / 325.6$	1. 2. 3.
s and 33	$P_{E(APP)}$	Appendage Drag, horsepower, $\{1\} \bullet \{12\} \bullet \{a\}^3 \bullet \{22\}$	1. 2. 3.
t and 34	$P_{E(AA)}$	Air Drag, horsepower, $\{14\} \bullet \{23\} \bullet \{a\}^2 / 96{,}500$	1. 2. 3.
u and 35	$P_{E(MISC)}$	Miscellaneous drag, horsepower,	1. 0.0 2. 0.0 3. 0.0
v	ΣP_E	Sum of Effective Horsepowers, $\{r\} + \{s\} + \{t\} + \{u\}$	1. 2. 3.
w	EHP	Total Effective Horsepower, $\{v\} \bullet \{24\}$	1. 2. 3.
x and 36	PC	Propulsive Coefficient, EHP/SHP	0.65
y	P_e $P_{Sthreshold}$ P_{SGoal}	Shaft Horsepower, $\{w\} / \{x\}$	1. 2. 3.
	$P_{Ir\ threshold}$ $P_{Ir\ goal}$	Needed Installed Shaft Horsepower $\{y\} \bullet 1.25$	2. 3.
	P_I	Total Installed Shaft Horsepower	

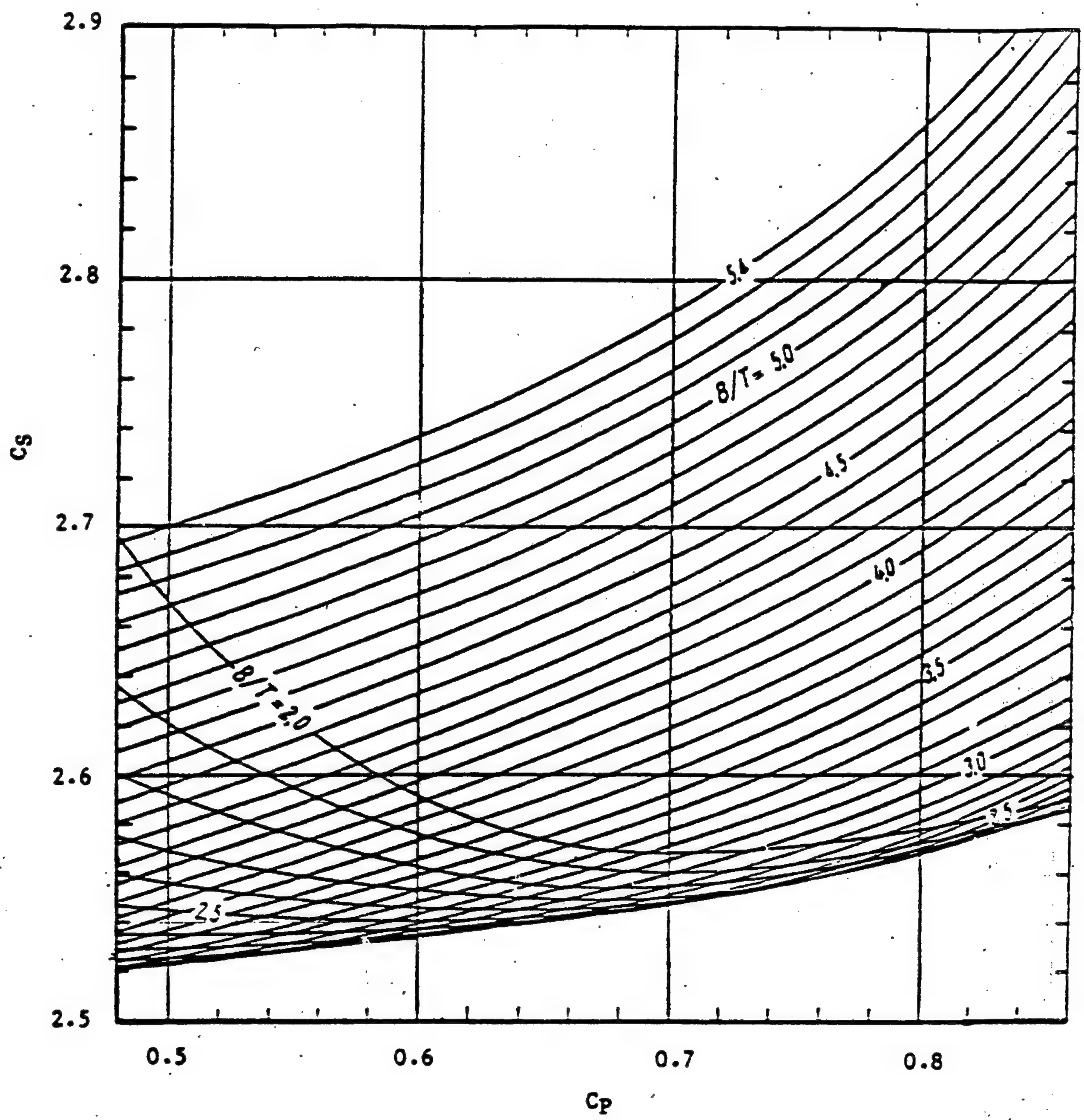


Figure 1 : Surface Coefficients $C_S = S / (Vol \cdot L_{WL})^{0.5}$ for the Taylor Standard Series

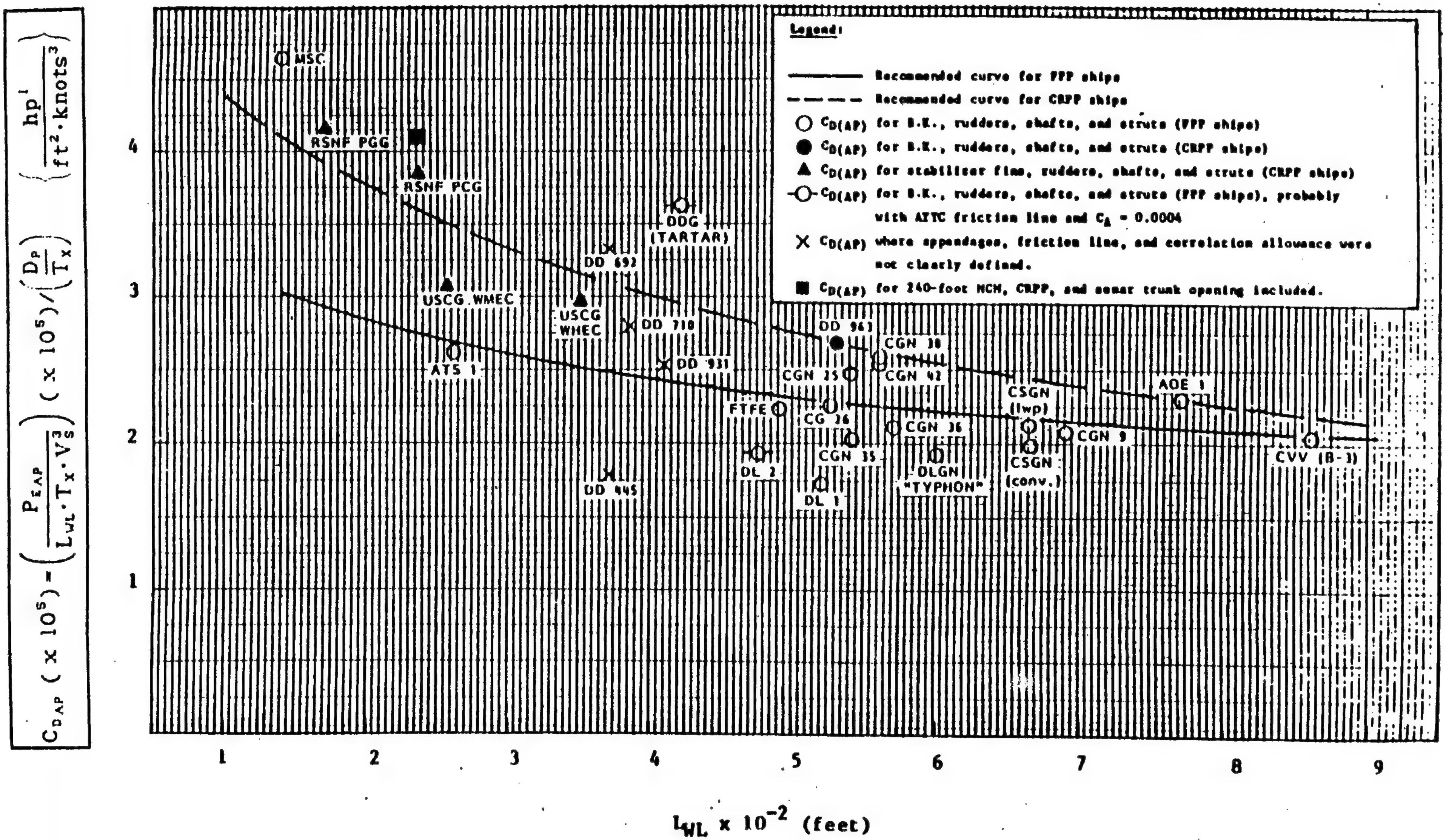


Figure 2 : Appendage Drag Coefficients For Twin-Screw Naval Ships With Strut-Supported Shafts

Sheet 1 of 2 : Plot

Notes:

1. $C_{D(AP)}$ values based on PE data calculated with ITTC friction line and $C_A = 0.0005$, except as noted.
2. When selecting the recommended curves for FPP ships, the "X" points were ignored.
3. When selecting the recommended curve for CRPP ships, the $C_{D(AP)}$ values for PCG and PGG were given more "weight" than $C_{D(AP)}$ values for WHEC and WMEC.
4. The two CSGN points represent model test data for two differenc hull forms.
5. Compared to the typical D_P/T_X value of ships represented on this plot, the D_P/T_X value of the AOE 1 is small.

Figure 2 : Sheet 2 of 2 : Notes

8

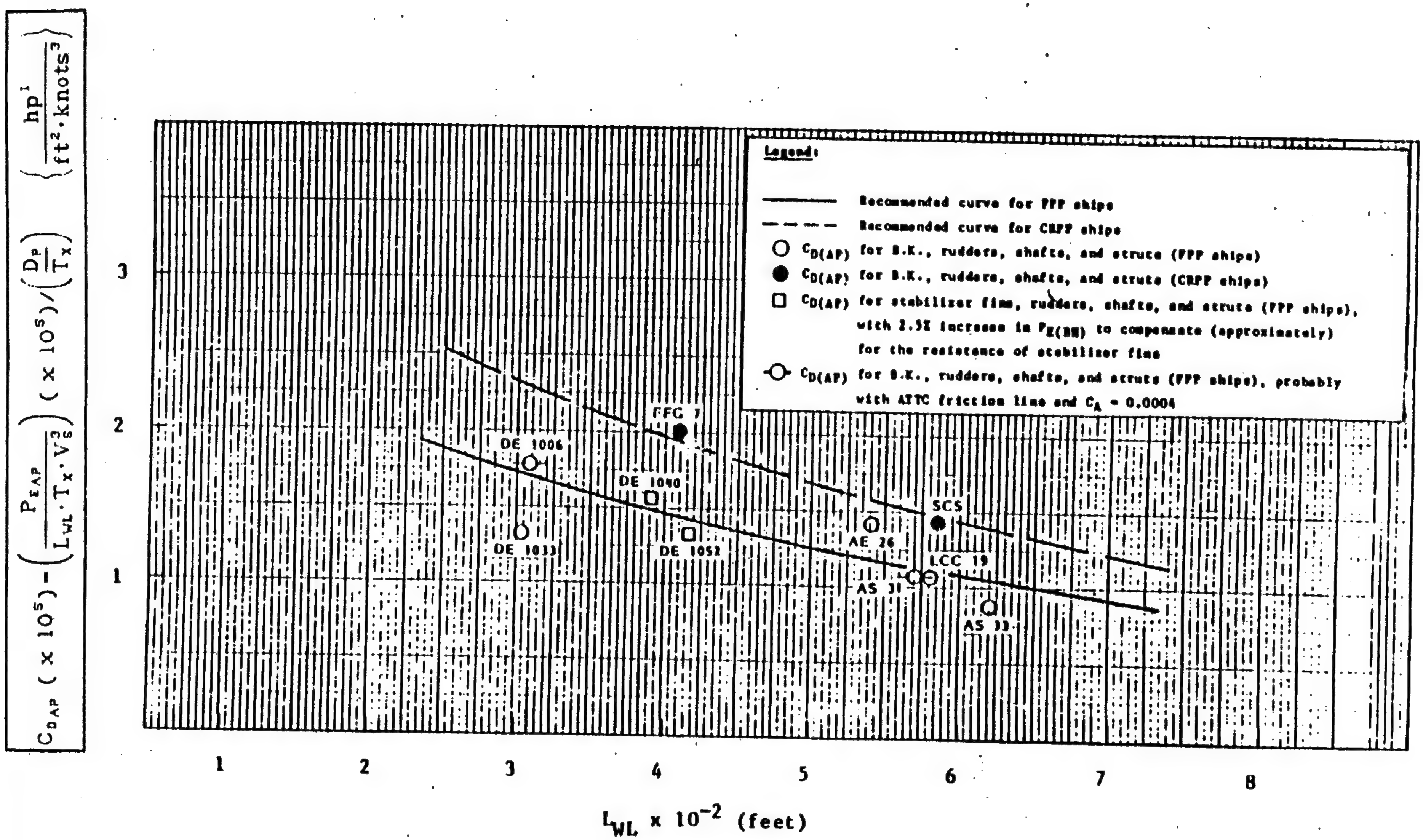


Figure 3 : Appendage Drag Coefficients for Single-Screw Naval Ships With Strut-Supported Shafts

Sheet 1 of 2 : Plot

Notes:

1. $C_{D(AP)}$ values based on P_E data calculated with ITTC friction line and $C_A = 0.0005$, except as noted.

2. $C_{D(AP)}$ value for the SCS is based on only three $P_{E(AP)}$ values at closely spaced speeds.

3. $C_{D(AP)}$ value for the DE 1006 may include the effect on appendage resistance of two small sound domes.

4. $C_{D(AP)}$ value for the FFG 7 includes the effect on appendage resistance of a skeg and a small, keel-mounted sound dome.

5. Compared to the typical D_P/T_X value of ships represented on this plot, the D_P/T_X value of the AE 26 is small.

Figure 3 : Sheet 2 of 2 : Notes

Taken From:
"Residuary Resistance Data for US Navy Destroyer-Type Hull Forms"
NAVSEA Report -3213-80-27, Dec 80.

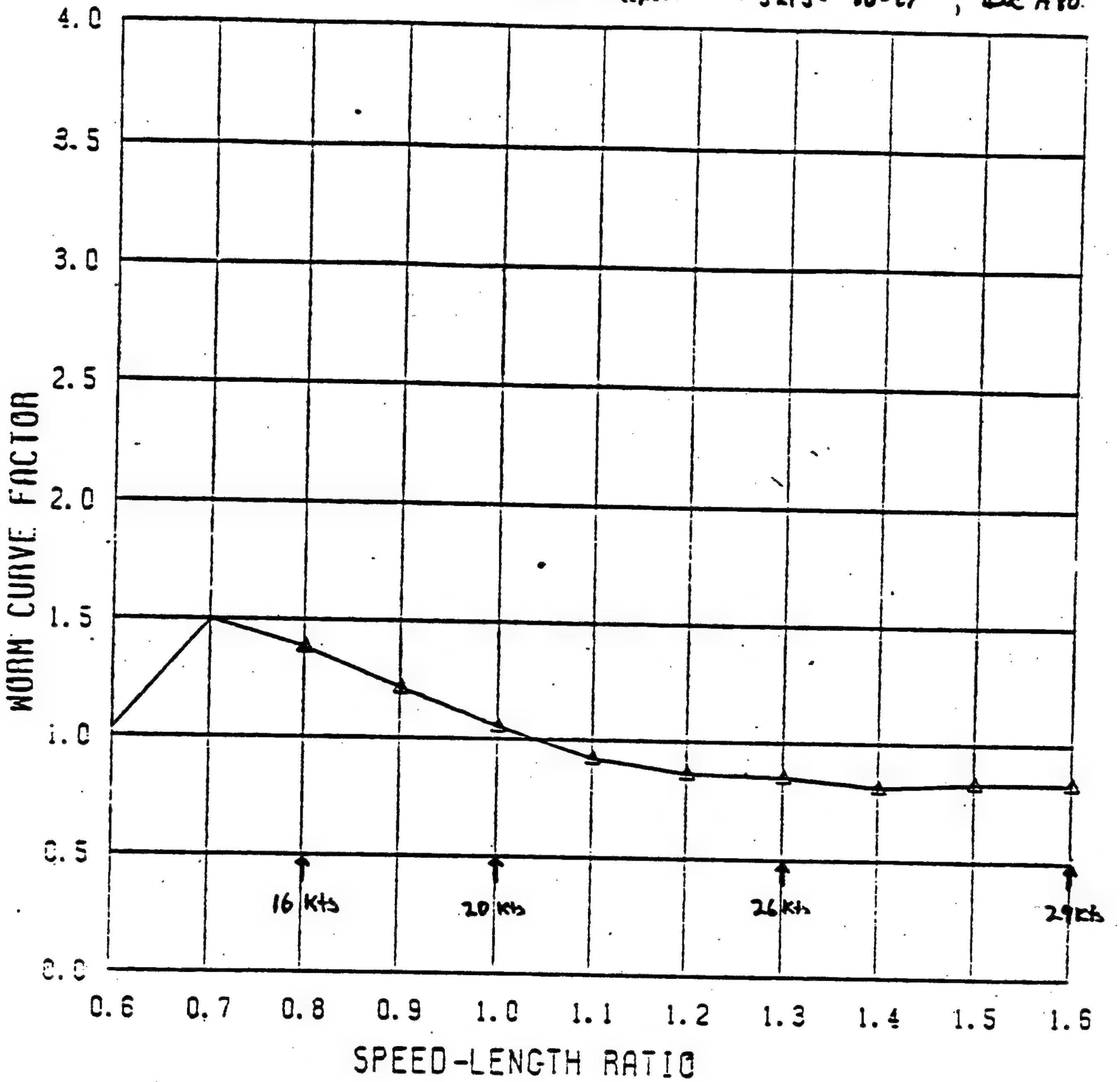


Figure 4 : Worm Curve of FFG-7 Hull Form

MODEL 5279

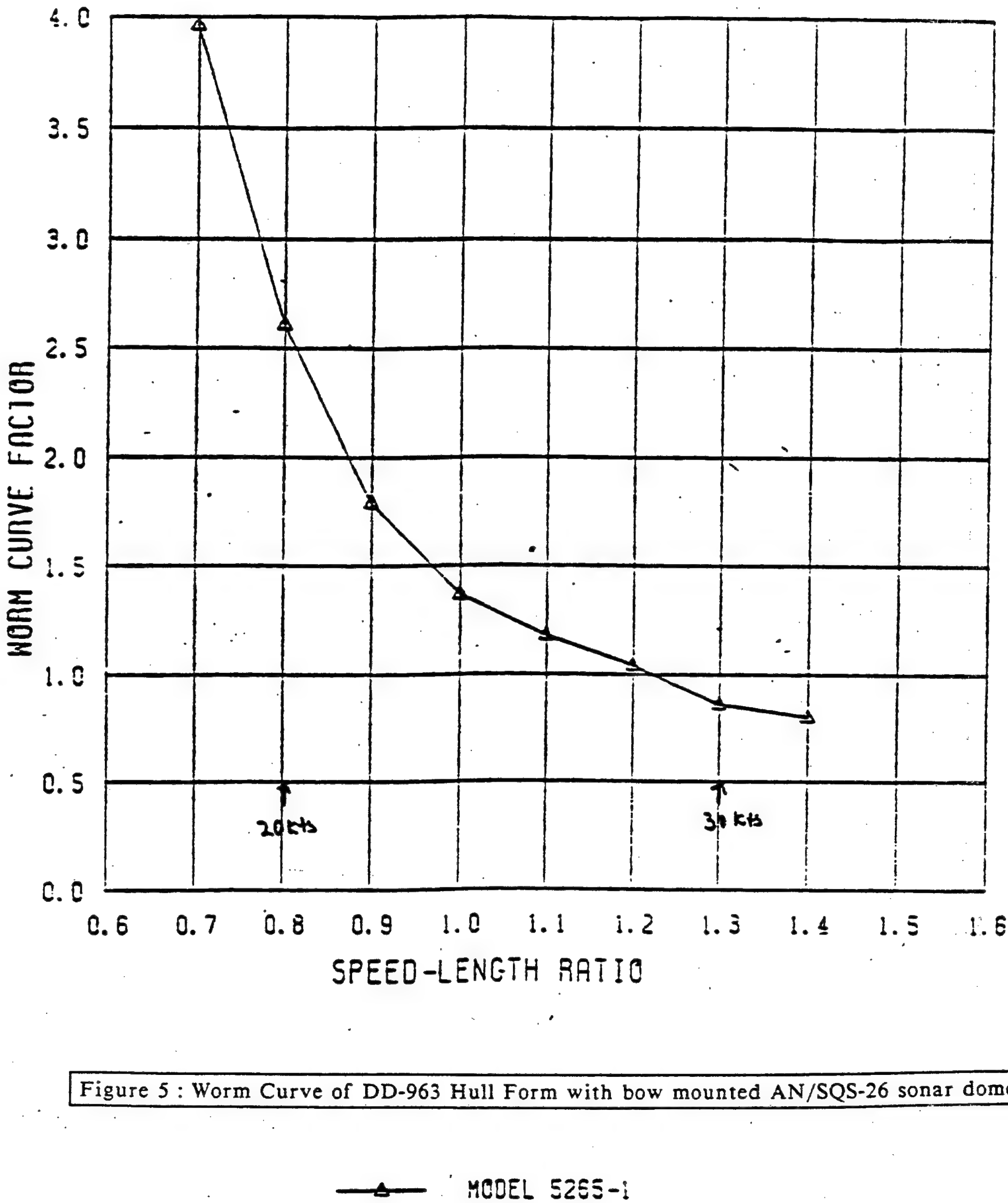


Figure 5 : Worm Curve of DD-963 Hull Form with bow mounted AN/SQS-26 sonar dome

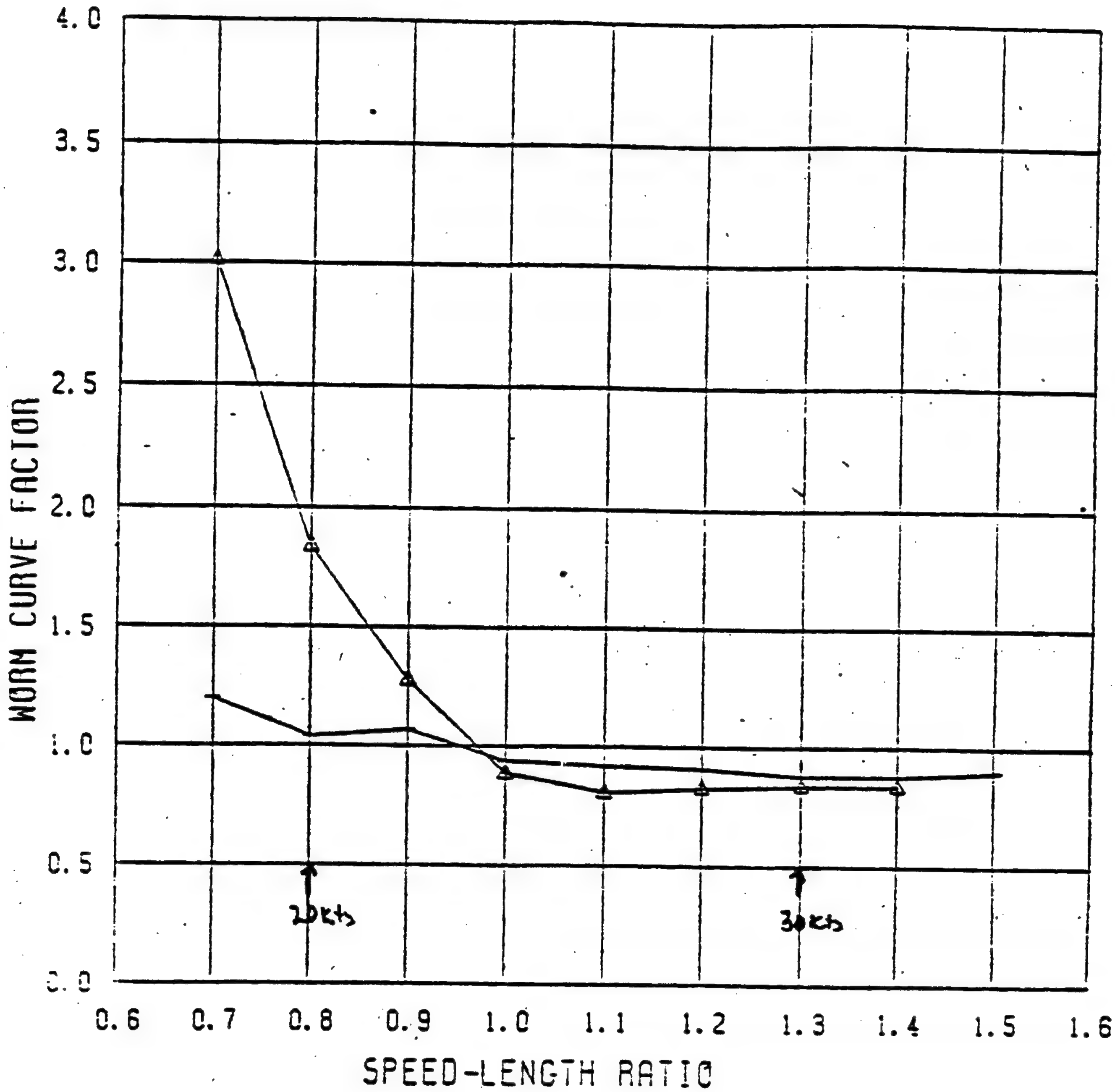
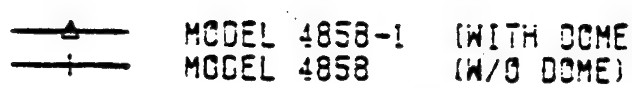


Figure 6 : Worm Curve of CG-26 Hull Form with and without bow mounted AN/SQS-26 sonar dome



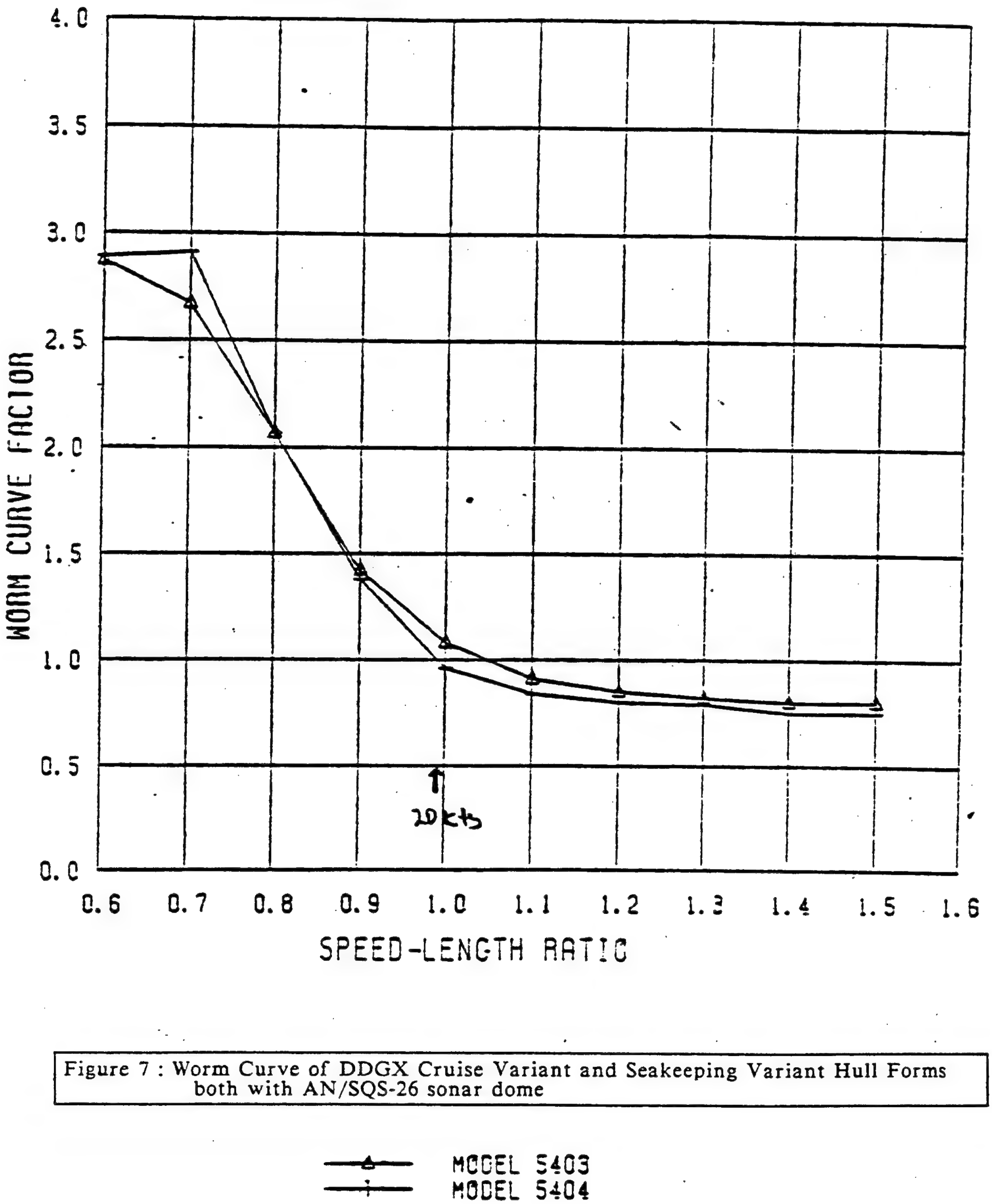


Figure 7 : Worm Curve of DDGX Cruise Variant and Seakeeping Variant Hull Forms both with AN/SQS-26 sonar dome

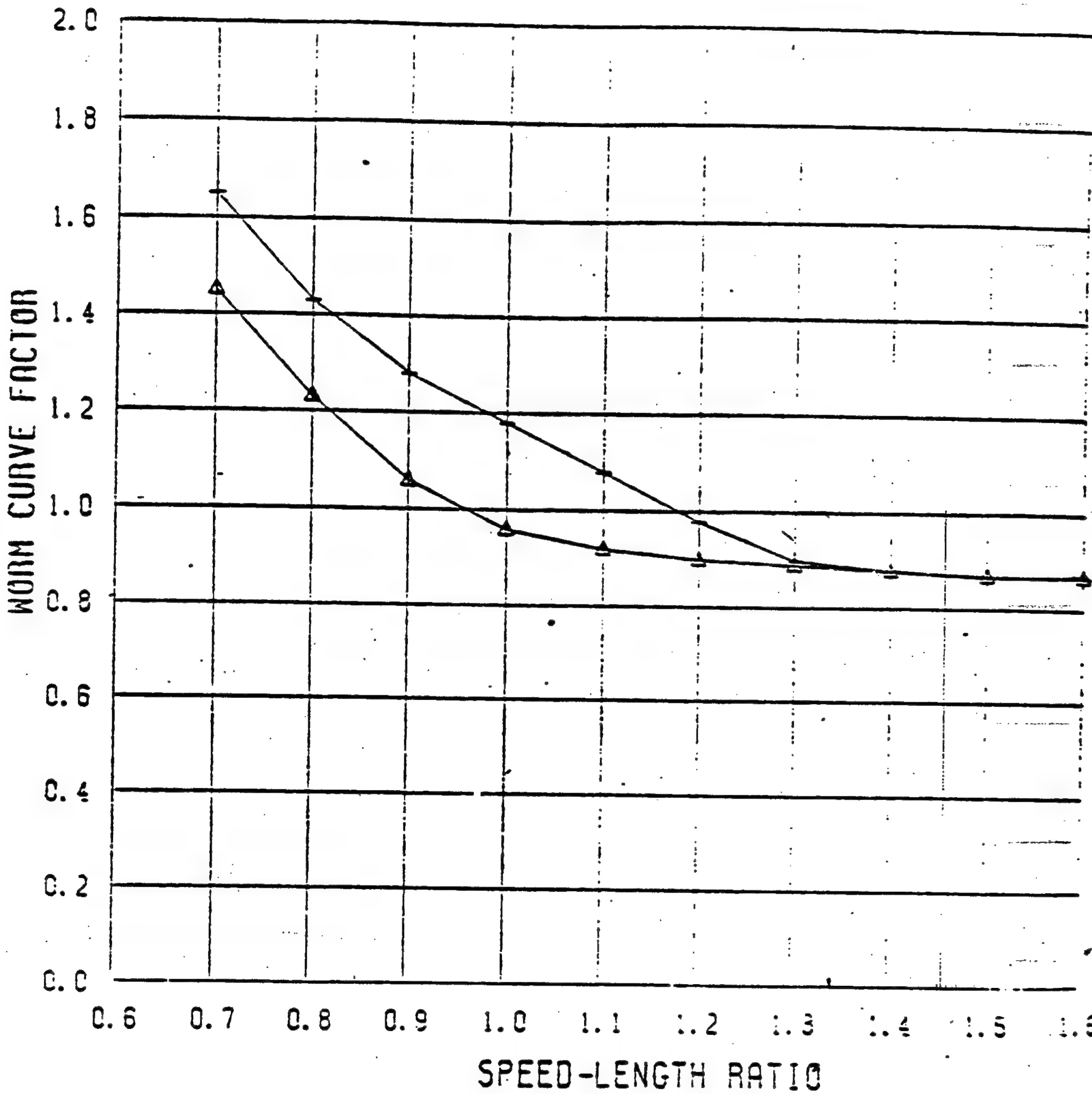
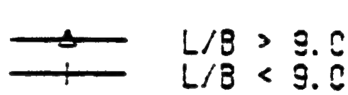


Figure 8 : Recommended Worm Curves for USN Destroyer Type Hull Form without bow dome



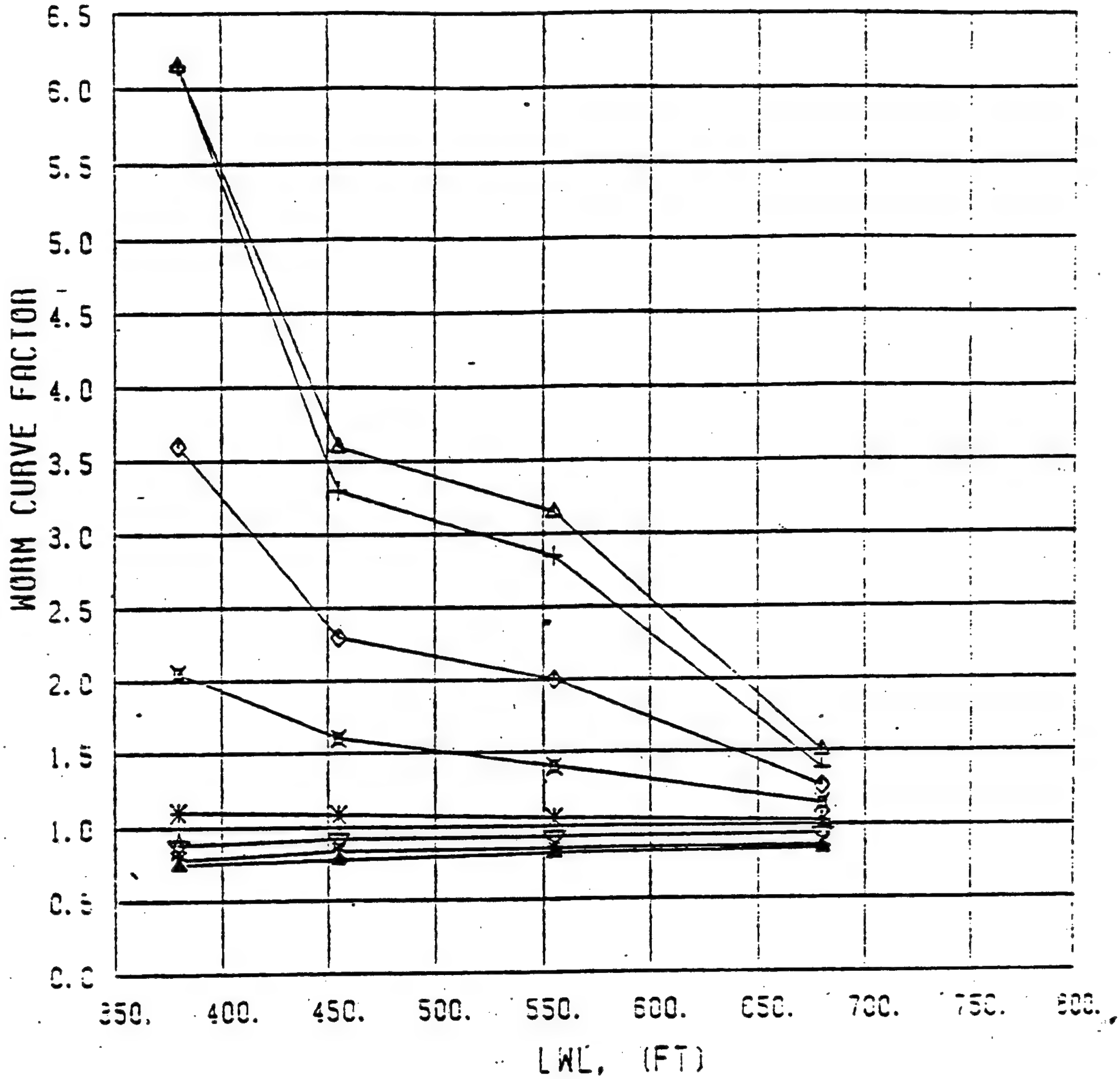
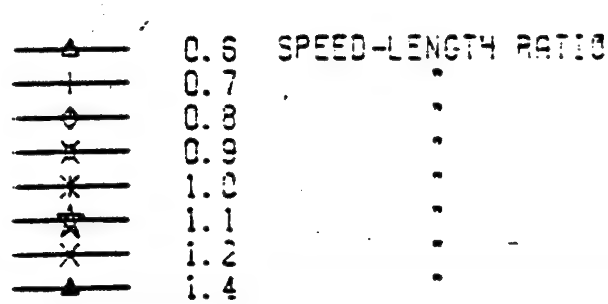


Figure 9 : Contours of recommended Worm Curve factor versus Ship Waterline length. For USN Destroyer Type Hull Forms with bow mounted AN/SQS-26 sonar dome



ENERGY BALANCE

VARIABLES USED.

SYMBOLS USED IN ENERGY BALANCE MODULE	
P_e	Endurance power, shaft horsepower
P_{eavg}	Average Endurance power, shaft horsepower
FR	Specific fuel consumption for engine, lb/hp-hr
F_I	Power ratio factor
FR_{SP}	Specified fuel rate
P_I	Installed power, shaft horsepower
FR_{avg}	Average Endurance fuel rate
E	Endurance distance, nautical miles
V_e	Endurance speed, knots
W_{BP}	Burnable propulsion endurance fuel weight
TPA	Tail pipe allowance, propulsion fuel
W_{FP}	Propulsion endurance fuel weight
γ	Specific fuel weight, propulsion
∇_{FP}	Propulsion fuel tankage volume
kW_{CL}	Connected Electrical load
kW_{MCL}	Maximum connected load
kW_{FL}	Functional load
kW_{MFL}	Maximum functional load
kW_{MFLm}	Maximum functional load with margin
n	Number of generators
kW_C	Electrical power of single generator
kW_I	Installed electrical power
kW_{24}	Average 24 hour electrical load
kW_{24avg}	Average 24 hour electrical load with margin
FR_e	Specific fuel consumption for generator, lb/kW-hr
f_{Ie}	Power ratio factor, electrical
$FR_{avg\ e}$	Average electrical fuel rate

W_{Be}	Burnable electrical endurance fuel weight
TPA_e	Tail pipe allowance, electrical fuel
W_{Fe}	Electrical endurance fuel weight
γ_e	Specific fuel weight, electrical
∇_{Fe}	Electrical fuel tankage volume
W_F	Total Fuel Weight
∇_F	Total propulsion and electrical fuel tankage volume

Calculations:

Propulsion Fuel

Average Endurance Power

$$\mathbf{P_{eavg} = 1.1 \bullet P_e}$$

where the 10% factor is for sea state, hull fouling, machinery degredation, etc.

Specified Fuel Rate

$$\mathbf{FR_{SP} = f_1 \bullet FR}$$

where f_1 factor is for instrumentation inaccuracies and machinery changes and is given by the following:

$$f_1 = \begin{bmatrix} 1.04 \ for \ \dfrac{P_e}{P_I} < \dfrac{1}{3} \\ 1.03 \ for \ \dfrac{P_e}{P_I} < \dfrac{2}{3} \\ 1.02 \ for \ \dfrac{P_e}{P_I} < 1 \end{bmatrix}$$

and FR is the Specified Fuel Consumption for the engine.

Average Endurance Fuel Rate

$$\mathbf{FR_{avg} = 1.05 \bullet FR_{SP}}$$

where 5% factor is for plant deterioration.

Burnable Propulsion Endurance Fuel Weight

$$W_{B_P} = \frac{E}{V_e}\cdot(P_{e_{avg}}\cdot FR_{avg})\cdot\frac{1}{2240}$$

Tail Pipe Allowance

$$TPA = \begin{bmatrix} 0.95 \text{ for broad, shallow tanks} \\ 0.98 \text{ for narrow, deep tanks} \end{bmatrix}$$

Propulsion Endurance Fuel Weight

$$W_{F_P} = \frac{W_{B_P}}{TPA}$$

Tankage Volume for Propulsion Fuel

$$\nabla_{FP} = 1.02 \bullet 1.05 \bullet \gamma \bullet W_{FP}$$

where the 5% factor is for fuel expansion and 2% is for the tank structure.

Electrical Load and Fuel

Estimate Maximum Functional Load with Margin

a. Estimate load for four conditions at two temperatures:

FILL IN LOAD kW_{CL}	10 °F	
Battle		
Cruise		
Anchor		
In Port		

and the largest of these loads is the maximum connected load, kW_{MCL}.

b. The functional load can be obtained by one of the following methods:

$$\text{Functional Load} = kW_{FL} = kW_{CL} \bullet \text{Load Factor (see DDS 9610-2)}$$

or from empirical formulas based on crew size, volume, payload, combat systems, etc. The maximum functional load is designated by kW_{MFL}

c. Maximum functional load with margin:

$$\mathbf{kW_{MFLm} = 1.2 \bullet 1.2 \bullet kW_{MFL}}$$

where the 20% factors are for acquisition (design and build) and service life margins.

Determine Installed Electrical Power

a. Generator size is obtained from the following formula:

$$kW_G \geq \frac{kW_{MFLm}}{(n-1)\cdot(0.9)}$$

where the n-1 factor is for one generator out of commission and the 0.9 factor is for generator control

b. Complete generator power installed is gotten from the following:

$$\mathbf{kW_I = n \bullet kW_G}$$

Estimate Average 24 hour Electrical Load

kW24 consists of the complete propulsion and steering loads required during cruise operations and 75% of all other cruise loads. Note that this does not contain any margins.

Average 24 hour Electrical Load with Margin

$$\mathbf{kW_{24avg} = 1.2 \bullet kW_{24}}$$

where the 20% factor is an acquisition margin.

Average Electrical Fuel Rate

$$FR_{avge} = 1.05\, f_{1e}\, FR_e$$

where the f_{1e} factor is for machinery changes and instrumentation inaccuracies and is given by the following:

$$f_{1_e} = \begin{bmatrix} 1.04 \textit{ for } \frac{P_e}{P_I} < \frac{1}{3} \\ 1.03 \textit{ for } \frac{P_e}{P_I} < \frac{2}{3} \\ 1.02 \textit{ for } \frac{P_e}{P_I} < 1 \end{bmatrix}$$

where P_e/P_I is defined in the following way for electric power:

$$\frac{P_e}{P_I} = \frac{kW_{24_{avg}}}{(n-1) \cdot kW_G}$$

FRe is the specified fuel consumption for a generator and the 5% factor is for plant deterioration.

Burnable Electrical Endurance Fuel Weight

$$W_{B_e} = \frac{E}{V_e} \cdot (kW_{24_{avg}} \cdot FR_{avg_e}) \cdot \frac{1}{2240}$$

Tail Pipe Allowance, Electrical

$$TPA_e = \begin{bmatrix} 0.95 \textit{ for broad, shallow tanks} \\ 0.98 \textit{ for narrow, deep tanks} \end{bmatrix}$$

Electrical Endurance Fuel Weight

$$W_{F_e} = \frac{W_{B_e}}{TPA_e}$$

Tankage Volume for Electrical Fuel

$$\nabla_{Fe} = 1.02 \cdot 1.05 \cdot \gamma \cdot W_{Fe}$$

where the 5% factor is for fuel expansion and the 2% is for tank structure.

Total Fuel Values

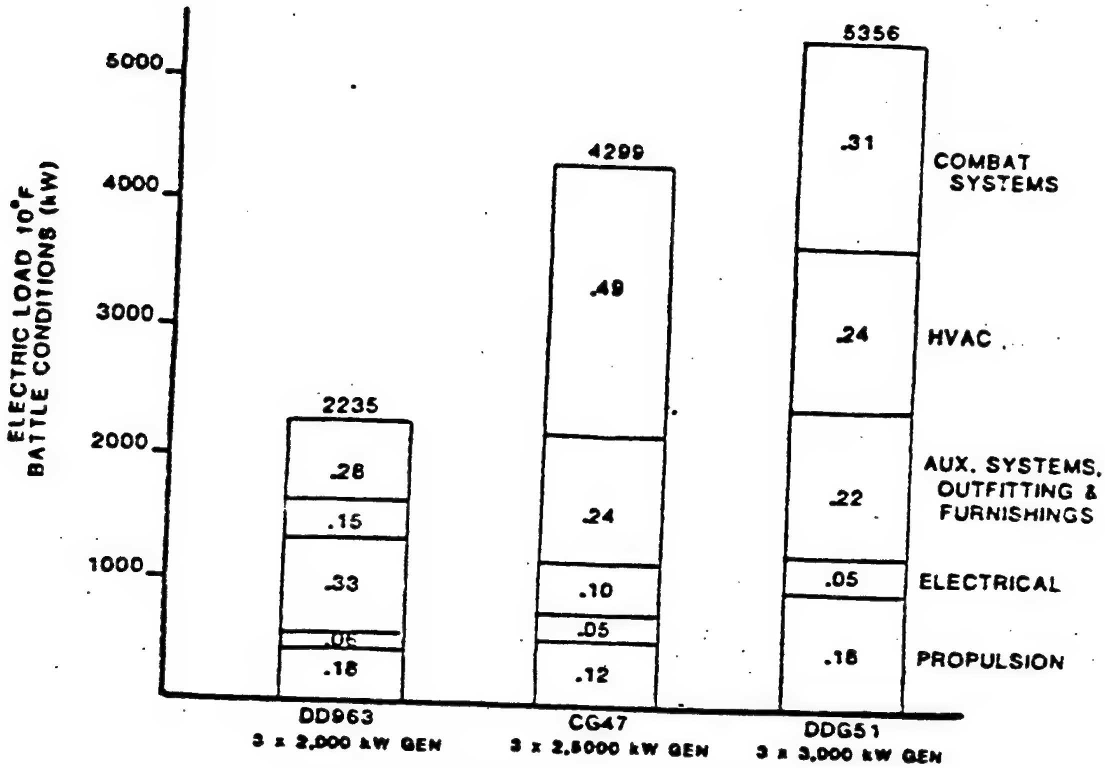
Total Fuel Weight

$$W_F = W_{FP} + W_{Fe}$$

Total Propulsion and Electrical Fuel Tankage

$$\nabla_F = \nabla_{FP} + \nabla_{Fe}$$

Fig 11 U.S. SHIPS – ELECTRICAL LOADS



FRIGATES —

Fig 12 INSTALLED POWER

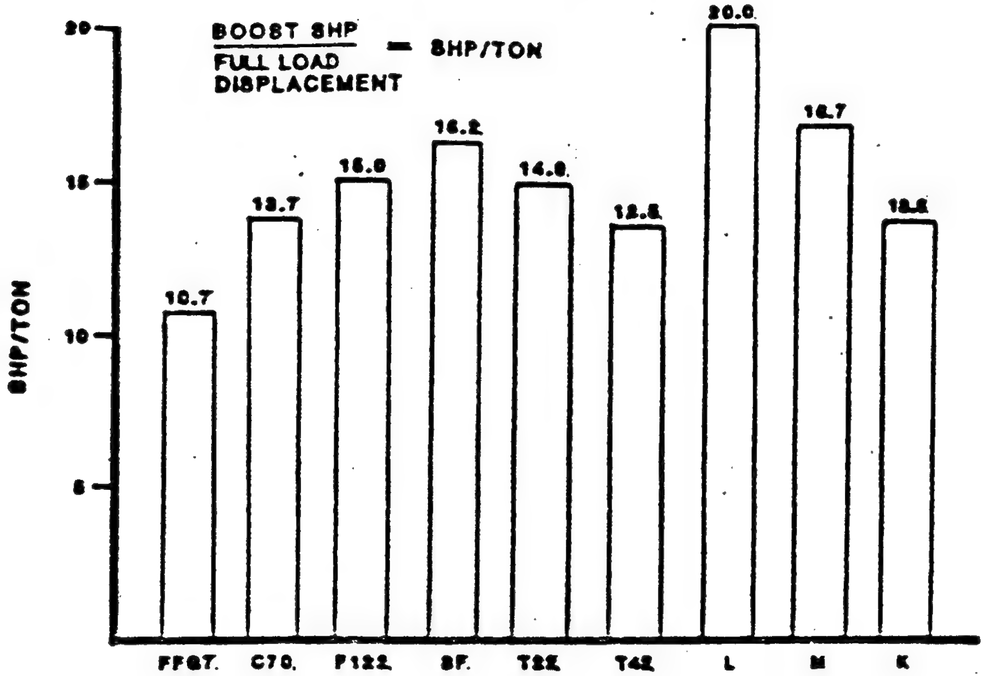
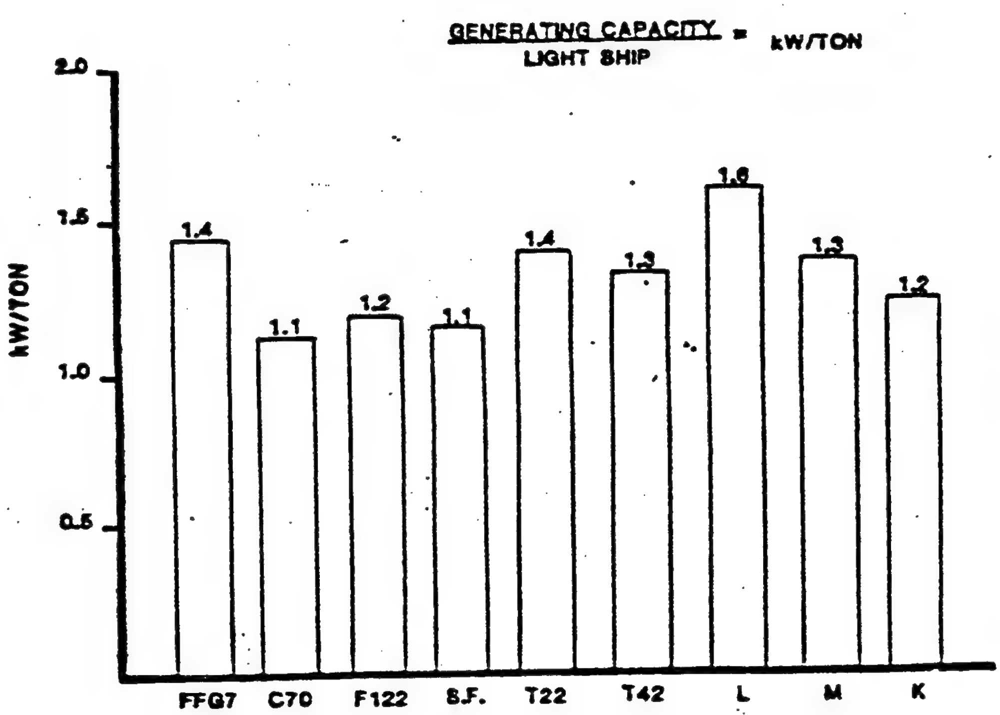


Fig 13 FRIGATES – ELECTRICAL CAPACITY



APPENDIX D. MATLAB OPTIMIZATION COMPUTER PROGRAM

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This MATLAB program initiates the use of the optimization toolbox for%
% a constrained, non-linear problem.  Two input arrays from the Mathcad%
% worksheet (w,z) are used in conjunction with the user defined design %
% space boundaries (vlb,vub) and initial design variable guess (x0).   %
% These are passed to the optimizer (constr), which determines the     %
% minimum full load displacement and the values of the design variables%
% at that point.                                                       %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

w=in0;                    %Input weight array from Mathcad%

z=in2;                    % Input values for # of personnel, speed and
                          % endurance%

options(1)=1;             %Toggles on optimizer output summary%

diary outopt              % Saves optimizer input/output details to
                          % MATLAB editor%

x0=[in1(1),in1(2),in1(3),.6,.75]     % Initial guess of B,T,LWL,Cp,Cx
                                     % from Mathcad%
%x0=[0,0,0,0,0]                    %Use different intial guess to check
                                   %if local minimum.

vlb=[20,5,200,.54,.7]    %Upper and Lower bounds of design variables%
vub=[90,30,800,.64,.85]

[x,options]=constr('disp3opt',x0,options,vlb,vub,[],w,z)

diary off

optctr=options(10)         % Counter for number of optimization
                           % iterations%

B=x(1)
T=x(2)
LWL=x(3)
cp=x(4)
cx=x(5)

[Wfl,g,Cgmb]=disp3opt(x,w,z);

Cbt=x(1)/x(2);
Clb=x(3)/x(1);
Cdispl=Wfl/((x(3)/100)^3);

out0=[Wfl,x,Cbt]';
out1=[Cbt,Clb,Cgmb,Cdispl,optctr]';
```

```
function [Wf41,Dp]=resist_calc(x,z)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This function calculates the hull resistance, the propulsion power %
% and the electrical service load required to generate the necessary %
% fuel load as part of the full load displacement calculation.  The  %
% resistance calculation uses Gertler's reanalysis of the Taylor     %
% Standard Series. The designer must ensure that the following       %
% variables are properly assigned to remain consistent with the      %
% Mathcad model;  FR                                                  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%RESISTANCE AND PROPULSION POWER CALCULATION%

Cpropd=z(9);                   %Cpropd=1.2 for one prop, 1.0 for two props%
Dp=(.662*x(2)+.012*x(3))*Cpropd;  %Prop diameter%
Aw=x(1)*(3*x(2));                 %Frontal Area of Ship%

roair=.0023817;  Tsw=59;  rosw=1.995; nusw=1.2817e-5; %Physical
hp=33000/60;        lton=2240;      knt=1.69;         %Properties

Ca=.0005;        %Correlation allowance%
Cstss=2.53;      %Wetted surface coefficient, average value%

volfl=x(1)*x(2)*x(3)*x(4)*x(5);   %Underwater volume%

Ss=Cstss*sqrt(volfl)*sqrt(x(3));  %Wetted surface area%

Cdapp=2.85*hp*1e-5/knt^3;         %Appendage drag coefficient%
Caa=.7;                           %Air drag coefficient%
PMF=1.1;                          %Power Margin Factor%

Ve=z(3)*knt                      %Endurance speed%
Vs=z(2)*knt                      %Sustained speed%
E=z(4)*knt                       %Endurance range%

for i=1:7
   V(i)=i*5*knt;
   V(4)=Ve;                       %Endurance speed%
   V(6)=Vs;                       %Sustained speed%

   R(i)=(V(i)/sqrt(x(3)))/knt;    %Speed-to-length ratio%
   Rn(i)=x(3)*V(i)/nusw;          %Reynolds Number%
   Cf(i)=.075/(log10(Rn(i))-2)^2;
   Rf(i)=.5*(rosw*Ss*(V(i))^2*(Ca+Cf(i))); %ITTC Friction%

   %Taylor Resistance Coefficient for interpolation of Cr%
   Cr225=[.00028 .00028 .00028 .0008 .00150 .00335 .00410];
   Cr300=[.00035 .00035 .00042 .001 .0018 .0035 .0043];
   Cr375=[.00048 .00048 .00048 .00095 .0018 .0036 .0046];

   FF=(4/3)*((x(1)/x(2))-3);                          %Form Factor%

   Crtss(i)=Cr300(i)+FF*((Cr375(i)-Cr225(i))/2)+FF^2*...
         ((Cr225(i)+Cr375(i))/2-Cr300(i));
   Rrtss(i)=.5*(rosw*Ss*V(i)^2*Crtss(i));             %TSS Resistance%

   WCF=[3.242 2.124 1.460 1.083 .923 .880 .870];  %Worm Curve Factor%

   Rr(i)=Rrtss(i)*WCF(i);
```

```
   Rt(i)=Rf(i)+Rr(i);

   Pebh(i)=Rt(i)*V(i)/hp;      %Bare hull effective horsepower%
   Csd=.28; Asd=z(5);          %Sonar Dome, SQS-53C=215ft, SQS-56=27ft%
   Peapp(i)=(x(3)*Dp*Cdapp+.5*Csd*rosw*Asd)*(V(i)^3)/hp; %Appendage HP%
   Peaa(i)=.5*Caa*Aw*roair*V(i)^3/hp;  %Air resistance horsepower%
   Pet(i)=(Pebh(i)+Peapp(i)+Peaa(i));
   EHP(i)=PMF*Pet(i);                   %Total effective horsepower%

   PC=.67;              %Propulsive Coefficient%
   SHP(i)=EHP(i)/PC;    %Shaft horsepower%
end

Pe=SHP(4);              %Endurance shaft horsepower%
Ps=SHP(6);              %Sustained speed shaft horsepower%
Pireq=1.25*Ps;          %Required installed horsepower%
Npeng=z(10);            %Number of engines installed%
Pbeng=z(11);            %Engine horsepower%
Pibrake=Npeng*Pbeng;    %Installed BHP%

%PROPULSION FUEL WEIGHT CALCULATION%

Pebavg=(1.1*Pe)/.97;    %Average endurance BHP required, w/fouling%
FR=1.97*Pebavg^(-.15);%Specific fuel rate, GT. (Diesel=.327, ICR=.347)%
f1=1.04;                %Margin for instrumentation differences%
FRsp=f1*FR;             %Specified fuel rate%
FRavg=1.05*FRsp;        %Average fuel due to plant deterioration%
Wbp=(E/Ve)*Pebavg*FRavg/lton;%Burnable propulsion endurance fuel wt%
Wfp=Wbp/.95;            %Tailpipe allowance%
gammaf=43;              %Fuel specific volume%
Vfp=1.02*1.05*gammaf*Wfp;  %Propulsion fuel volume%

%ELECTRICAL LOAD CALCULATION%

Nt=z(1);                           %# of personnel%
kWfins=z(7);                       %Stabilizing fin power%

kWp=.00466*Pibrake;                %Propulsion electrical load%
kWs=.00583*x(3)*x(2);              %Steering electrical load%
kWl=.0002053*1.8*x(1)*x(2)*x(3); %Lighting electrical load%
kWm=46.1;                          %Miscellaneous load%
kWh=.0013*1.25*x(1)*x(2)*x(3);    %Heating electrical load%
kWcps=.00026*1.8*x(1)*x(2)*x(3); %CPS electrical Load%
kWv=.19*(kWh+kWp)+kWcps;           %Ventilation electrical load%
kWac=.67*(.1*Nt+.0015*.47*1.3*x(1)*x(2)*x(3)+.1*kWp);  %A/C load%
kWb=.94*Nt;                        %Aux boiler and FW%
kWf=.0001*1.8*x(1)*x(2)*x(3);     %Firemain load%
kWrh=.00002*1.25*x(1)*x(2)*x(3); %Unrep and handling load%
kWa=.22*Nt+kWfins;                 %Aux machinery load%
kWserv=.35*Nt;                     %Service and work space load%

%Non-payload functional load%
kWnp=kWp+kWs+kWl+kWm+kWh+kWcps+kWv+kWac+kWb+kWf+kWrh+kWa+kWserv;

kWpay=z(6);                      %Payload power%
kWmfl=kWpay+kWnp;                  %Maximum functional load%
kWmflm=1.2*1.2*kWmfl;              %With margins%

kW24=.5*(kWmfl-kWp-kWs)+.8*(kWp+kWs);  %24 hr electrical load%
kW24avg=1.2*kW24;                      %With margins%
```

```
%ELECTRICAL FUEL RATE%

FRg=.113;                         %Specific fuel rate for generators%
FRgsp=f1*FRg;                     %With margins%
FRgavg=1.05*FRgsp;                %Plant deterioration%

Wbe=(E/Ve)*(kW24avg*FRgavg)/lton;%Burnable electric fuel weight%
Wfe=Wbe/.95;                      %Tank allowance%
Vfe=1.02*1.05*gammaf*Wfe;         %Electrical Fuel volume%

Wf41=Wfp+Wfe;                     %Total ship fuel weight, lton%
Vf=Vfp+Vfe;                       %Total ship fuel volume%
```

```
function [CN,D10,Vd,Vt]=cubicnum_calc(x)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This function calculates the cubic number and the depth of the    %
% midships section.  The total volume is calculated from the        %
% sum of the underwater and deckhouse volumes.  The deckhouse volume %
% can be calculated using a range of values to fit the requirement. %
% The designer must ensure that the calculation of Vd is consistent %
% between this M-file and the Final Synthesis Design Mathcad        %
% Worksheet.                                                        %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%CALCULATE CUBIC NUMBER%

%Sheer Line%

M=[.21*x(1)+x(2), x(3)/15, 22];
D10min=max(M);
D10=D10min+1;
D0=1.0111827*x(2)-(6.36215e-6*x(3)^2)+(2.780649e-2*x(3))+x(2);
D20=.014*x(3)*(2.125+(1.25e-3*x(3)))+x(2);

%Above Water Hull Volume%

F0=D0-x(2);
F10=D10-x(2);
F20=D20-x(2);

Apro=x(3)*(F0+4*F10+F20)/6;
Fav=Apro/x(3);

Dav=Fav+x(2);

CN=x(3)*x(1)*Dav/1e5;            %Cubic Number%

Cw=.236+.836*x(4);

ff=.714599+.18098*Dav/x(2)-.018828*(Dav/x(2)).^2;  %Flare factor%

Mf=[ff 1];    ff=max(Mf);

Vhaw=x(3)*x(1)*Fav*Cw*ff;
Vfl=x(1)*x(2)*x(3)*x(4)*x(5);       %Underwater volume%

Vht=Vfl+Vhaw;

Vd=.0025*x(3)^3;                    %Deckhouse volume, max calc%
%Vd=.0005*x(3)^3;                   %Deckhouse volume, min calc%

Vt=Vht+Vd;                          %Total ship volume%
```

```
function [Wdvd,W24,Wls,w]=dvd_weights(x,Dp,CN,Vd,Vt,w,z)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This function calculates the design variable dependent weights and %
% the light ship weight.                                              %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% DESIGN VARIABLE DEPENDENT WEIGHTS %

lton=2240;                                    %Long ton conversion factor%
Nt=z(1);                                      %Number of Personnel%
Npeng=z(10);                                  %Number of propulsion engines%
Pbeng=z(11);                                  %Engine horsepower%
Np=z(12);                                     %Numper of propellers%
Pinst=Npeng*Pbeng*.97;                        %Installed power%
fs=z(13);                                     %.5 twin screws,.33 single%
W237=w(7);                                    %APU weight%
Wbm=Pinst*(9+12.4*((Pinst*1e-5)-1)^2)/lton;%Propulsion weight%
Ws=.356*x(3)*fs;                              %Shaft weight%
Wpr=(Np*.05575*Dp^(5.497-.0433*Dp))/lton;%Propeller weight%
Wb=.15*(Ws+Wpr);                              %Bearing weight%
Wst=Ws+Wpr+Wb;                                %Total Shafting weight%
W2=Wbm+W237+Wst;                              %Total propulsion weight%

Waux=(.00072*Vt^1.443+5.14*Vt+6.19*Vt^.7224+377*Nt+2.74*Pinst)*...
   1e-4+113.8;                  %Auxiliary machinery weight
w(13)=Waux;
W598=.000075*Vt;                %Auxiliary machinery fluid weight%
W5=Waux+W598;

W6=(31.4+.0003187*Vt);          %Wofh, hull fitting weights%
w(15)=W6;

Wic=4.65*CN;                    %Gyro/Nav/IC%
w(9)=Wic;

Wco=2.24*CN;                    %Other Group 400%
w(10)=Wco;

Wcc=.04*(w(25)+Wic+Wco);        %Cabling Weight%
w(11)=Wcc;

W4=w(25)+Wic+Wco+Wcc+w(12);     %Intermediate Weight Group Sum%

Wbh=.93*(1.68341*CN^2+167.1721*CN-103.283); %Bare Hull Weight%
w(1)=Wbh;

rodh=.001429;                   %Deckhouse density, steel%
Wdh=rodh*Vd;                    %Deckhouse weight
w(2)=Wdh;

W171=.0688*x(3)-13.75;          %Mast Weight%
w(4)=W171;

W180=.0675*Wbm+.072*(w(8)+W4+W5+w(32));  %Foundation Weights%
w(3)=W180;

W1=Wbh+Wdh+W171+W180;

Wvpw=w(24)-w(17)-w(18)-w(19)-w(33);  %Subtract out variable payloads%
```

```
Wm24=0.1*(Wvpw+W1+W2+W4+W5+W6);  %10% Weight Margin for Future Growth%

Wdvd=W1+W2+W4+W5+W6+Wm24;          %Design Variable Dependent Weights%
W24=Wdvd-Wm24+Wvpw;
Wls=Wdvd+Wvpw                      %Lightship weight%
```

```
function GM=stability_calc(x,w,f,D10,Wls,W24)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This function uses the previously calculated full load displacement %
% to generate stability data and return the value of GM for the      %
% constraint requirements.                                             %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%  STABILITY CALCULATION  %

Vfl=x(1)*x(2)*x(3)*x(4)*x(5);%Underwater volume%

%CALCULATE MOMENTS%

P(1)=w(1)*.527*D10;            %Bare hull weight%
P(2)=w(2)*(D10+1.5*9);         %Deckhouse weight%
P(3)=w(3)*.68*D10;             %Foundation weight%
P(4)=w(4)*2.65*D10;            %Mast weight%
P(5)=w(5)*.5*D10;              %Propusion machinery weight%
P(6)=w(6)*(3.9+.19*x(2));      %Shafting weight%
P(7)=w(7)*w(30);               %APU weight%
P(8)=w(8)*.65*D10;             %Electric generator weight%
P(9)=w(9)*D10;                 %Gyro/IC/Nav weight%
P(10)=w(10)*(5.6+.4625*D10);   %Misc group 400 weight%
P(11)=w(11)*.5*D10;            %Cabling weight%
P(12)=w(12)*w(31);             %Sonar dome weight%
P(13)=w(13)*.9*(D10-7.4);      %Auxiliary weight%
P(14)=w(14)*.5*D10;            %Aux steam weight%
P(15)=w(15)*.805*D10;          %Hull fitting weight%
P(16)=w(16)*(8+.71*D10);       %Personnel misc%

P(17)=w(17)*.746*D10;          %Crew weight%
P(18)=w(18)*.55*D10;           %Provision weight%
P(19)=w(19)*.65*D10;           %General stores%
P(20)=w(20)*7.5;               %Fuel weight%
P(21)=w(21)*10;                %Helo fuel weight%
P(22)=w(22)*.35*D10;           %Lube oil weight%
P(23)=w(23)*7.5;               %Potable water weight%

ww=w(26)*w(28)-w(27)*w(29);
px=sum(P(1:16));
Pwg=px+ww;

KGls=Pwg/W24;
Pwgl=sum(P(17:23))+w(27)*w(29);
Wl=sum(w(17:23))+w(33);
VCGl=Pwgl/Wl;

KG=(((Wls*KGls)+(Wl*VCGl))/f)+.5;

Cw=.236+.836*x(4);
Cit=-.497+1.44*Cw;

KB=(x(2)/3)*(2.5-(x(4)*x(5)/Cw));

BM=(x(3)*x(1)^3*Cit)/(12*Vfl);

GM=KB+BM-KG;
```

APPENDIX E. MATHCONNEX INTEGRATED SHIP DESIGN SYSTEM VALIDITY AND ROBUSTNESS CHECKS

Design Attribute	Initial Run			Expand Side Constraints			High Value Initial Guess		
	Results	vlb-vub	x0	Results	vlb-vub	x0	Results	vlb-vub	x0
Displacement, Wfl (lton)	6123.424			6123.424			6123.424		
Beam, B (ft)	45.50163	40 to 70	55.745	45.50163	20 to 90	55.745	45.50163	20 to 90	100
Draft, T (ft)	12.29774	10 to 30	16.892	12.29774	5 to 40	16.892	12.29774	5 to 40	100
Waterline Length, LWL (ft)	455.0163	400 to 700	495.3	455.0163	200 to 800	495.3	455.0163	200 to 800	1000
Prismatic Coefficient, Cp	0.54	.54 to .64	0.6	0.54	.54 to .64	0.6	0.54	.54 to .64	10
Max Transverse Section, Cx	0.787983	.70 to .85	0.75	0.787983	.70 to .85	0.75	0.787983	.70 to .85	10
Beam-to-Draft, Cbt	3.7			3.7			3.7		
Length-to-Beam, Clb	10			10			10		
GM-to-Beam, Cgmb	0.122			0.122			0.122		
Displacement-to-Length, Cdl	65			65			65		
Number of Iterations	31			31			109		

Design Attribute	Low Value Initial Guess			Constrainted Above Optimum			Constrained Below Optimum		
	Results	vlb-vub	x0	Results	vlb-vub	x0	Results	vlb-vub	x0
Displacement, Wfl (lton)	6123.424			7182.628			4729.255		
Beam, B (ft)	45.50163	40 to 70	0	50	50 to 90	55.745	40.22113	20 to 90	55.745
Draft, T (ft)	12.29774	10 to 30	0	15	15 to 40	16.892	10.41899	5 to 10	16.892
Waterline Length, LWL (ft)	455.0163	400 to 700	0	500	500 to 800	495.3	406.4662	200 to 800	495.3
Prismatic Coefficient, Cp	0.54	.54 to .64	0	0.54	.54 to .64	0.6	0.121007	.54 to .64	0.6
Max Transverse Section, Cx	0.787983	.70 to .85	0	0.770449	.70 to .85	0.75	0.281007	.70 to .85	0.75
Beam-to-Draft, Cbt	3.7			3.333333			3.860366		
Length-to-Beam, Clb	10			10			10.10579	Warning: No feasible solution found.	
GM-to-Beam, Cgmb	0.122			0.122			-0.33549		
Displacement-to-Length, Cdl	65			57.46102			70.42378		
Number of Iterations	49			32			37		

Results of Optimizer Validity and Robustness Checks.

MATLAB OPTIMIZER DETAILED OUTPUT FOR VALIDIDTY AND ROBUSTNESS CHECKS:

Initial Run Results:

```
x0 =  55.7451    16.8924   495.3014     0.6000     0.7500

vlb = 40.0000    10.0000   400.0000     0.5400     0.7000

vub = 70.0000    30.0000   700.0000     0.6400     0.8500

f-COUNT    FUNCTION         MAX{g}          STEP  Procedures
    6       7627.82       0.534195            1
   12        6312.8      0.0459915            1
   18       6099.97     0.00388632            1
   24       6123.31  1.92403e-005             1
   30       6123.42  6.04933e-010             1    Hessian modified
   31       6123.42  8.88178e-016             1    Hessian modified
Optimization Converged Successfully
Active Constraints:
     2
     4
     6
     8

x =  45.5016    12.2977   455.0163     0.5400     0.7880
```

Expand Side Constraints:

```
x0 =  55.7451    16.8924   495.3014     0.6000     0.7500

vlb = 20.0000     5.0000   200.0000     0.5400     0.7000

vub = 90.0000    40.0000   800.0000     0.6400     0.8500

f-COUNT    FUNCTION         MAX{g}          STEP  Procedures
    6       7627.82       0.534195            1
   12        6312.8      0.0459915            1
   18       6099.97     0.00388632            1
   24       6123.31  1.92403e-005             1
   30       6123.42  6.04933e-010             1    Hessian modified
   31       6123.42  8.88178e-016             1    Hessian modified
Optimization Converged Successfully
Active Constraints:
     2
     4
     6
     8

x = 45.5016    12.2977   455.0163     0.5400     0.7880
```

High Value Initial Guess:

x0 = 100 100 1000 10 10

vlb = 20.0000 5.0000 200.0000 0.5400 0.7000

vub = 90.0000 40.0000 800.0000 0.6400 0.8500

f-COUNT	FUNCTION	MAX{g}	STEP	Procedures
6	26700.1	0.244444	1	infeasible
12	23210.4	-0.00381213	1	
19	19983	-0.00179031	0.5	
26	11608.4	-0.03448	0.5	
33	7598.42	-0.0343611	0.5	
40	6651.19	-0.0150468	0.5	
47	6359.78	-0.0075712	0.5	
54	6236.04	-0.00384339	0.5	
61	6178.47	-0.00194103	0.5	
68	6150.64	-0.000975889	0.5	
75	6136.96	-0.000489382	0.5	
82	6130.17	-0.000245074	0.5	
89	6126.79	-0.00012263	0.5	
96	6125.11	-6.13377e-005	0.5	
102	6123.42	6.05291e-008	1	
108	6123.42	1.36113e-013	1	Hessian modified twice
109	6123.42	0	1	Hessian modified twice

Optimization Converged Successfully
Active Constraints:
2
4
6
8

x = 45.5016 12.2977 455.0163 0.5400 0.7880

Low Value Initial Guess:

x0 = 0 0 0 0 0

vlb = 20.0000 5.0000 200.0000 0.5400 0.7000

vub = 90.0000 40.0000 800.0000 0.6400 0.8500

f-COUNT	FUNCTION	MAX{g}	STEP	Procedures
6	3317.57	5.37994	1	
12	3686.38	5.72939	1	
18	4293.17	0.774454	1	
24	5199.71	0.23014	1	
30	5911.86	0.0398647	1	
36	6113.23	0.00179708	1	
42	6123.4	4.04898e-006	1	
48	6123.42	1.33333e-011	1	Hessian modified
49	6123.42	3.77476e-015	1	Hessian modified

Optimization Converged Successfully
Active Constraints:
2
4
6
8

x = 45.5016 12.2977 455.0163 0.5400 0.7880

Constrained Above Optimum:

```
x0 =  55.7451   16.8924  495.3014    0.6000    0.7500

vlb = 50.0000   15.0000  500.0000    0.5400    0.7000

vub = 90.0000   40.0000  800.0000    0.6400    0.8500

f-COUNT   FUNCTION         MAX{g}         STEP  Procedures
    6      7712.59      0.508232            1
   12      7188.86             0            1
   19      7185.72             0          0.5
   25      7182.61    0.00010248            1
   31      7182.63 2.87194e-009             1   Hessian modified
   32      7182.63 1.55431e-015             1   Hessian modified
Optimization Converged Successfully
Active Constraints:
     4
     6

x = 50.0000   15.0000  500.0000    0.5400    0.7704
```

Constrained Below Optimum:

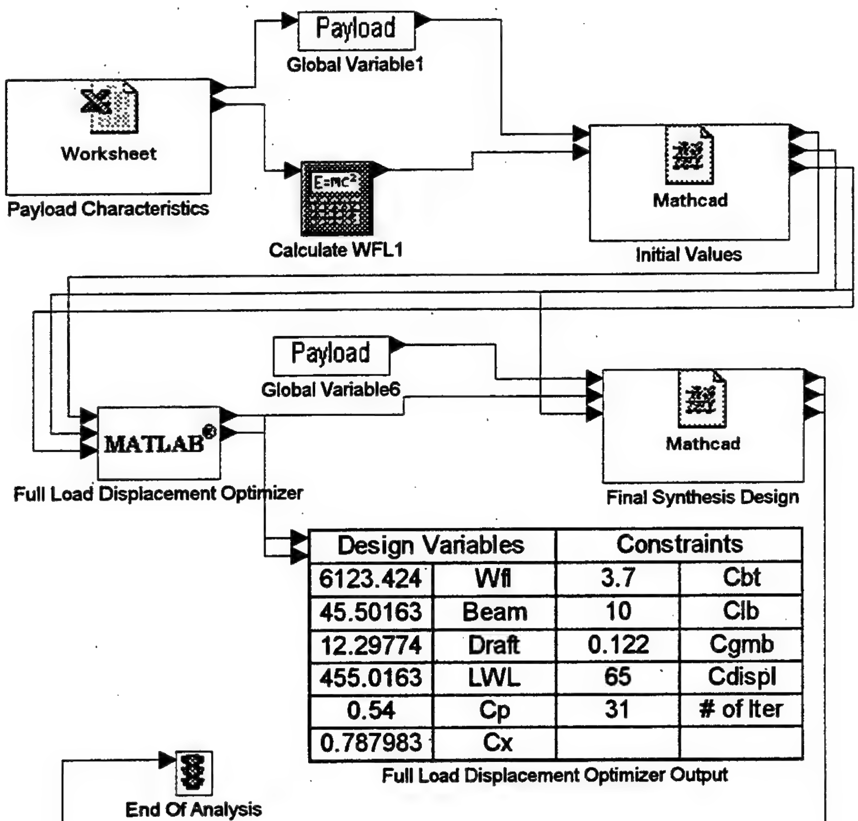
```
x0 =  55.7451   16.8924  495.3014    0.6000    0.7500

vlb = 20.0000    5.0000  200.0000    0.5400    0.7000

vub = 90.0000   10.0000  800.0000    0.6400    0.8500

f-COUNT   FUNCTION         MAX{g}         STEP  Procedures
    6       6906.3       1.70751            1   infeasible
   12      4987.11      0.801315            1   infeasible
   18      4738.86     0.0763757            1   infeasible
   24       4729.4      0.083331            1   infeasible
   30      4729.26     0.0834429            1   Hessian modified twice;
infeasible
   36      4729.26     0.0834426            1   Hessian modified;
infeasible
   37      4729.26     0.0834427            1   Hessian modified;
infeasible
Warning: No feasible solution found.

x = 40.2211   10.4190  406.4662    0.1210    0.2810
```

APPENDIX F. OPTIMIZED AND NON-OPTIMIZED DESIGN EXAMPLE RESULTS

This section contains:

- The ISDS MathConnex worksheet
- The Excel spreadsheet of the characteristics for the DD-13A Payload #2
- The Initial Value Mathcad Math Model
- The Matlab Optimizer detailed output
- The Final Design Synthesis Mathcad Math Model
- The Non-Optimized MathConnex worksheet
- The Non-Optimized MIT Math Model

INTEGRATED SHIP DESIGN SYSTEM



Design Variables		Constraints	
6123.424	Wfl	3.7	Cbt
45.50163	Beam	10	Clb
12.29774	Draft	0.122	Cgmb
455.0163	LWL	65	Cdispl
0.54	Cp	31	# of Iter
0.787983	Cx		

Full Load Displacement Optimizer Output

Design Variables		Design Checks		Stability, Payload, $	
6131.108	Wfl	102626	Pinstalled	5.57727	GM
45.50163	Beam	60939.77	Prequired	18.38554	KG
12.29774	Draft	3000	kWinstld	7.71077	KB
455.0163	LWL	2006.707	kWreqrd	16.25204	BM
0.54	Cp	3.078702	Area Error	1.23E-01	Cgmb
0.787983	Cx	-0.12534	Wgt Error	10.91383	Payload %
3.7	Cbt			1017.818	Cost, $Mil
10	Clb				

Final Design Summary

DD13A
PAYLOAD #2

PAYLOAD NAME	WT KEY	WT	VCG DATUM	VCG FT AD	AREA KEY	HULL FT2	DKHS FT2	CRUISE KW	BATTLE KW
STEEL LANDING PAD [ON HULL] - SH-60 CAPABLE	W111	10.7	36.717	0.20	NONE	0	0	0	0
128 CELL VLS ARMOR - LEVEL III HY-80									
VGAS HY-80 ARMOR LEVEL II									
SQS-53C 5M BOW SONAR DOME	W165	85.7	0	-1.5	NONE	0	0	0	0
GROUP 100	WP100	96.4				0	0	0	0
CIC W/UYQ-44 & 2X LSD	W410	19.34	0	35.58	A1131	1953	448	45.03	45.03
NAVIGATION SYSTEM	W420	7.29	51	14.00	A1132	0	848.3	55.99	53.5
ADVANCED DIGITAL C4I (JTIDS/LINK 16/LINK22/TADIXS/TACINTEL)	W440	37.91	51	-46.84	A1110	1230.6	1270.4	35.76	39.67
SPS-67 SURFACE SEARCH RADAR	W451	1.81	51	-10.00	A1121	0	70	8	0
ADVANCED IFF	W455	2.32	51	-5.00	NONE	0	0	3.2	4
SPY-1D MFAR – SINGLE TRANSMITTER									
X-BAND RADAR AND FOUNDATION, 110 FT ABOVE BL	W456	4.11	0	113.00	NONE	0	0	220.16	220.16
SQS-53C 5M BOW SONAR DOME ELEX	W463	57.7	0	9.3	A1122	1942	0	39	39
LIGHTWEIGHT BROADBAND VARIABLE DEPTH SONAR (LBVDS)									
SSQ-61 BATHYTHERMOGRAPH									
SQQ-28 SONOBUOY PROCESSING SYSTEM	W466	5.26	51	-44.86	NONE	0	0	1.15	1.15
ADVANCED INTEGRATED ELECTRONIC WARFARE SYSTEM (AIEWS)									
AN/SLQ-25A NIXIE	W473	0.24	36.717	-6.20	A1142	200	0	3	4.2
MK36 DLS W/6 LAUNCHERS	W474	0.96	33.4	5.39	NONE	0	0	2.4	2.4
MINEHUNTING AUV / REMOTE MINEHUNTING SYSTEM									
AEGIS-BASED VGAS GFCS [UYQ-21 + UYK-44]									
AN/SWG-1 HARPOON CONTROL IN CIC	W482	1.14	38.31575	10.80	NONE	0	0	0	4.9
MK99 GMFCS W/CEC W/3 SPG-62 ILLUM									
VLS WEAPON CONTROL SYSTEM	W482	0.7	38.31575	-7.80	A1220	56	310	13.62	19.69
ADVANCED TACTICAL WEAPON CONTROL SYSTEM (ATWCS)									
ASW CONTROL SYSTEM w/SSTD [ASWCS]									
COMBAT DF	W495	8.26	33.4	21.00	A1141	0	448	15.47	19.34
ELECTRONIC TEST & CHECKOUT	W499	1.1	38.31575	10.80	NONE	0	0	0	0
GROUP 400	WP400	148.14				5381.6	3394.7	442.78	453.04
FWD 64-CELL VLS MAGAZINE DEWATERING SYSTEM	W529	7	35.0585	-0.46	NONE	0	0	0	0
AFT 64-CELL VLS MAGAZINE DEWATERING SYSTEM									
COOLING EQUIPMENT FOR SPY-1D									
COOLING ADJUSTMENT FOR X-BAND RADAR	W532	4.43	0	9.81	A1121	47.85	0	13.64	13.64
LAMPS MKIII AVIATION FUEL SYS	W542	4.86	35.0585	-11.00	A1380	30	0	2	2.9
LAMPS MKIII RAST/RAST CONTROL/HELO CONTROL	W588	31.1	35.0585	-1.60	A1312	219	33	4.4	4.4
GROUP 500	WP500	47.39				296.85	33	20.04	20.94
SQS-53C 5M BOW SONAR DOME HULL DAMPING	W636	6.7	0	-2.5	NONE	0	0	0	0
LAMPS MKIII AVIATION SHOP AND OFFICE	W665	1.04	35.0585	-4.50	A1360	194	75	0	0
GROUP 600	WP600	7.74				194	75	0	0
VGAS 155 MM									
2X HARPOON SSM QUAD CANNISTER LAUNCHERS	W721	4.1	33.4	1.17	A1220	0	0	0	1.6
FWD MK41 VLS 64-CELL	W721	107.72	35.0585	1.14	A1220	128	0	69.65	69.65
AFT MK41 VLS 64-CELL									
2X MK32 SVTT ON DECK	W750	5.55	33.4	2.20	A1244	0	368	2	5
GROUP 700	W7	117.37				128	368	71.65	76.25
VGAS AMMO – 680 RDS									
HARPOON MISSILES – 8 RDS IN CANNISTERS	WF21	3.78	33.4	5.00	NONE	0	0	0	0
AFT MK 41 LAUNCHER MISSILE LOADOUT (ESSM, SM. VLA, TLAM, ATACMS)									
FWD MK 41 LAUNCHER MISSILE LOADOUT (ESSM, SM, VLA, TLAM, ATACMS)	WF21	144	35.0585	0.34	A1220	1420	720	0	0
MK46 LWT ASW TORPEDOES – 6 RDS IN SVTT TUBES	WF21	1.36	33.4	2.50	A1240	368	0	0	0
MK36 DLS SRBOC CANNISTERS - 100 RDS	WF21	2.2	33.4	11.60	NONE	0	0	0	0
SMALL ARMS AMMO - 7.62MM + 50 CAL + PYRO	WF21	4.1	33.4	-6	NONE	0	0	0	0
LAMPS MKIII 18 X MK46 TORP & SONOBUOYS & PYRO	WF22	9.87	35.0585	4.80	A1374	0	588	0	0
LAMPS MKIII 2 X SH-60B HELOS, UAV'S, AND HANGAR (BASED)	WF23	12.73	35.0585	4.50	A1340	0	3406	5.6	5.6
LAMPS MKIII AVIATION SUPPORT AND SPARES	WF26	9.42	35.0585	5.00	A1390	357	0	0	0
BATHYTHERMOGRAPH PROBES									
GROUP WF20	WF20	187.46				2145	4714	5.6	5.6
LAMPS MKIII:AVIATION FUEL (JP-5)	WF42	63.8	0	10.4	A1380	0	0	0	0
VARIABLE MILITARY PAYLOAD (WF20+WF42)	WVP	251.26							
ARMAMENT (WP500,WP600,W7,WF20)						2763.9	5190		
								KWP	
TOTAL PAYLOAD	WP	668.3				8145.5	8584.7	540.07	555.83
DATUM DEFINITIONS:									
	DEPTH0	47.445		VCG P:	24.78				
	DEPTH3	43.232		VCG VP:	29.61				
	DEPTH6.5	38.316							
	DEPTH10	33.4							
	DEPTH15	35.059							
	DEPTH20	36.717							
	BL	0							
	MAST BAS	51							

MIT MATH MODEL: INITIAL VALUES

$hp \equiv \frac{33000 \cdot ft \cdot lbf}{min}$ $\quad knt \equiv 1.69 \cdot \frac{ft}{sec}$ $\quad lton \equiv 2240 \cdot lb$

I. INPUT:

Primary Input Variables Are Highlighted in Yellow and Must Be Checked for Consistency Between MATHCAD Elements.

I1. Requirements:

Payload: **(From Excel Payload Spreadsheet)** $W_P := in0_1 \cdot lton$ **variable:** $W_{VP} := in0_2 \cdot lton$

Payload VCG: $VCG_P := in0_3 \cdot ft$ **Variable Payload VCG:** $VCG_{VP} := in0_4 \cdot ft$

Command and Surveillance Payload: **(W_{400} less 420 and 430)** $W_{P400} := in0_5 \cdot lton$

Armament (all W_{700}): $W_7 := in0_6 \cdot lton$ **Armor:** $W_{164} := in0_7 \cdot lton$

Mission handling/support: $W_{P500} := in0_8 \cdot lton$ **Mission outfit:** $W_{P600} := in0_9 \cdot lton$

Ordnance: $W_{F20} := in0_{10} \cdot lton$ **(incl helo wt, WF23)** **Helo Fuel:** $W_{F42} := in0_{11} \cdot lton$

Helo's: $N_{HELO} := 2$ $W_{F23} := 12.73 \cdot lton$

Payload Cruise Electric Power Requirement: $kW_{PAY} := in0_{12} \cdot kW$

Payload Deck Areas:

Deckhouse: **C&D:** $A_{DPC} := in0_{13} \cdot ft^2$ **(W400)**

Armament: $A_{DPA} := in0_{14} \cdot ft^2$ **(W500, W600, W700, WF20)**

Hull: **C&D:** $A_{HPC} := in0_{15} \cdot ft^2$ **(W400)**

Armament: $A_{HPA} := in0_{16} \cdot ft^2$ **(W500, W600, W700, WF20)**

Manning:

Officers: $N_O := 15$ **Enlisted:** $N_E := 135$ **Total:** $N_T := N_E + N_O$ $\quad N_T = 150$

Average deck height: $H_{DK} := 9 \cdot ft$

Sustained Speed: $V_S = 27 \cdot knt$ **(Use Figure 3 as a guide in selecting V_S)**

Endurance Speed: $V_e = 20 \cdot knt$ **Range:** $E = 7500 \cdot knt \cdot hr$

Stores period: $T_S := 45 \cdot day$

Sonar Dome/Appendages: **SQS-53C; 215ft^2, 87.9lton,-1.2ft,85.7lton SQS-56; 27ft ^{2},13.94lton,-3.1ft,7.43lton**

$A_{SD} := in2_5 \cdot ft^2$ **water:** $W_{498} := 87.9 \cdot lton$ $VCG_{498} := -1.2 \cdot ft$ **structure:** $W_{165} := 85.7 \cdot lton$

Fin Stabilizers: **(for one pair, electric power requirement = 50 kW)** $kW_{fins} := 0 \cdot kW$

Hull Material: (OS: C_{HMAT}=1.0; HTS: C_{HMAT}=0.93) $C_{HMAT} := .93$

CPS: (W_{CPS}=30lton): $W_{CPS} := 30 \cdot lton$ **(ie. no CPS)**

Machinery:

Number of propellers = $N_P := 2$ $C_{PROPD} := if(N_P > 1, 1.0, 1.2)$ $C_{PROPD} = 1$

Aux Propulsion (APU): $W_{237} := 0 \cdot lton$ $VCG_{237} := 0 \cdot ft$ **(Weight=14.2lton,VCG=3.5ft)**

Propulsion Engines (PE) - standard LM2500's; Generator engines; DDA 501-K34

Number and brake horsepower of propulsion engines: $N_{PENG} := 4$ $P_{BPENG} := 26450 \cdot hp$

Inlet/exhaust Xsect area for PE: $A_{IE} := 135.2 \cdot ft^2$ $A_{PIE} := N_{PENG} \cdot A_{IE}$ $A_{PIE} = 540.8 \cdot ft^2$

Deckhouse decks impacted by propulsion and generator inlet/exhaust: $N_{DIE} := 1$

Hull decks impacted by propulsion inlet/exhaust: $N_{HPIE} := 0$

Machinery Box: $H_{MBMIN} := 22 \cdot ft$ $L_{MB} := 40 \cdot ft$

$C_P = 0.59$ $C_{MB} := \dfrac{L_{MB}}{LWL}$ $C_{MB} = 0.081$ **C_{PMB} from Fig. 10:** $C_{PMB} := .998$

Ship Service Generators: $N_G := 3$ $kW_G := 3000 \cdot kW$

Hull decks impacted by generator inlet/exhaust: $N_{HeIE} := 1$

Specific fuel rate for generator engines: $FR_G := \dfrac{288}{2.54} \cdot \dfrac{lb}{kW \cdot hr}$ $FR_G = 0.085 \cdot \dfrac{lb}{hp \cdot hr}$

Inlet/exhaust X-sect area for gen: $A_{GIE} := 38.4 \cdot ft^2$ $A_{eIE} := N_G \cdot A_{GIE}$ $A_{eIE} = 115.2 \cdot ft^2$

II. GROSS CHARACTERISTICS

Hull Principle Characteristics:

(see Figures 5 and 6)

$LWL = 495.301 \cdot ft$ $B = 55.745 \cdot ft$ $C_P = 0.59$ $C_X = 0.85$

Adjust in Summary Section at end of file

deckhouse volume: $V_D = 97715 \cdot ft^3$ $C_{DHMAT} := 2$

(Deckhouse Material: Aluminum - C_{DHMAT}=1; Steel - C_{DHMAT}=2)

II1. Complete Principle Characteristics:

Choose Payload Weight Fraction from Figure 4 and Calculate Full Load Weight (1st Iteration only, set W_{FL}=W_{FL1} in Summary section at end of file).

$F_P := .1 \qquad W_{FL1} := \frac{W_P}{F_P} \qquad W_{FL1} = 6683 \cdot \text{lton}$

Specify Full Load Weight (subsequent iterations set W_{FL}=W_T from prior iteration in Summary at end of file):

$W_{FL} = 6683 \cdot \text{lton}$

Calculate Full Load Displacement and Volume at LWL:

$\Delta_{FL} := W_{FL} \qquad V_{FL} := \Delta_{FL} \cdot 35 \cdot \frac{ft^3}{lton} \qquad V_{FL} = 233905 \cdot ft^3$

Calculate Draft (LWL):

$T := \frac{V_{FL}}{C_P \cdot C_X \cdot LWL \cdot B} \qquad T = 16.892 \cdot ft$

II2. Calculate Displacement to Length Ratio and Compare to Figure 5:

$C_{\Delta L} := \frac{\Delta_{FL}}{\left(\frac{LWL}{100}\right)^3} \qquad C_{\Delta L} = 55 \cdot \frac{lton}{ft^3}$ **(45-65)**

II3. Calculate Speed to Length Ratio and C_V:

$R_{VL} := \frac{V_S}{\sqrt{LWL}} \quad R_{VL} = 1.213 \cdot \frac{knt}{ft^{.5}} \qquad C_V := \frac{V_{FL}}{LWL^3} \quad C_V = 0.001925$

II4. Calculate Beam to Draft Ratio and Compare to Tables 1-4:

$C_{BT} := \frac{B}{T} \qquad C_{BT} = 3.3$ **(2.8-3.7)**

II5. Calculate Length to Beam Ratio:

$C_{LB} := \frac{LWL}{B} \qquad C_{LB} = 8.885$ **(7.5-10)**

III. ENERGY (Uses Taylor Standard Series (TSS)

References: DDS 051-1 and Taylor Reanalysis by Gertler

III1. Calculate TSS Resistance:

III1.1 Estimate propeller diameter and frontal area of ship:

$C_{PROPD} = 1 \qquad D_P := (.662 \cdot T + .012 \cdot LWL) \cdot C_{PROPD} \qquad D_P = 17.126 \cdot ft$

Frontal area of ship = $A_W := B \cdot (3 \cdot T) \qquad A_W = 2825.012 \cdot ft^2 \qquad \rho_A := .0023817 \cdot \frac{slug}{ft^3}$

III1.2 Seawater properties:

$T_{SW} := 59$ $\rho_{SW} := 1.9905 \cdot \frac{slug}{ft^3}$ $\nu_{SW} := 1.2817 \cdot 10^{-5} \cdot \frac{ft^2}{sec}$

III1.3 Resistance calculation parameters:

Correlation Allowance: $C_A := .0005$

$C_P = 0.59$

Use Figure 7 with C_P and C_{BT} for TSS wetted surface coeficient: $C_{STSS} := 2.536$

$C_{BT} = 3.3$

$S_{TSS} := C_{STSS} \cdot V_{FL}^{.5} \cdot LWL^{.5}$ $S_{TSS} = 27296.301 \cdot ft^2$

Specify or estimate actual ship surface area: $S_S := S_{TSS}$

Use Figure 8 or 9 with LWL for Appendage Drag Coeficient: $LWL = 495.301 \cdot ft$

$C_{DAPP} := 2.85 \cdot \frac{hp \cdot 10^{-5}}{ft^2 \cdot knt^3}$

Air Drag Coeficient: $C_{AA} := .7$

Power Margin Factor (margin for concept design = 10%): $PMF := 1.05$

III1.4 Use range of ship speeds for speed to length ratios (R_i). Reynold's numbers (RN_i) and ITTC friction (RF_i):

$i := 1 .. 7$ $V_i := i \cdot 5 \cdot knt$ **Ensure range includes V_e and V_S:** $V_6 := V_S$ $V_6 = 27 \cdot knt$

$V_4 := V_e$ $V_4 = 20 \cdot knt$

$R_i := \frac{V_i}{\sqrt{LWL}}$ $R_{N_i} := LWL \cdot \frac{V_i}{\nu_{SW}}$ $C_{F_i} := \frac{.075}{\left(\log\left(R_{N_i}\right) - 2\right)^2}$

$R_{F_i} := .5 \cdot \left[\rho_{SW} \cdot S_S \cdot \left(V_i\right)^2 \cdot \left(C_A + C_{F_i}\right)\right]$

$\frac{V_i}{knt}$	$R_i \cdot \frac{ft^{.5}}{knt}$	R_{N_i}	C_{F_i}	$\frac{R_{F_i}}{lbf}$
5	0.225	$3.265 \cdot 10^8$	0.002	4398.533
10	0.449	$6.531 \cdot 10^8$	0.002	16409.293
15	0.674	$9.796 \cdot 10^8$	0.002	35518.594
20	0.899	$1.306 \cdot 10^9$	0.001	61486.466
25	1.123	$1.633 \cdot 10^9$	0.001	94155.526
27	1.213	$1.763 \cdot 10^9$	0.001	109072.521
35	1.573	$2.286 \cdot 10^9$	0.001	179157.237

III1.5 Use Gertler with C_P, C_V, R_i and C_{BT} to interpolate for C_R and calcualte TSS resistance:

$C_P = 0.59 \qquad C_V = 0.001925$

C_{BT}=2.25 $\qquad$ C_{BT}=3.00 $\qquad$ C_{BT}=3.75

$$R_i \cdot \frac{ft^{.5}}{knt} = \begin{bmatrix} 0.225 \\ 0.449 \\ 0.674 \\ 0.899 \\ 1.123 \\ 1.213 \\ 1.573 \end{bmatrix} \qquad C_{R2.25} := \begin{bmatrix} .00028 \\ .00028 \\ .00028 \\ .00080 \\ .00150 \\ .00335 \\ .00410 \end{bmatrix} \qquad C_{R3.00} := \begin{bmatrix} .00035 \\ .00035 \\ .00042 \\ .00100 \\ .00180 \\ .00350 \\ .00430 \end{bmatrix} \qquad C_{R3.75} := \begin{bmatrix} .00048 \\ .00048 \\ .00048 \\ .00095 \\ .00180 \\ .00360 \\ .00460 \end{bmatrix}$$

Form Factor: $\quad FF := \frac{4}{3} \cdot (C_{BT} - 3) \qquad FF = 0.4$

$$C_{RTSS_i} := C_{R3.00_i} + FF \cdot \left(\frac{C_{R3.75_i} - C_{R2.25_i}}{2} \right) + FF^2 \cdot \left(\frac{C_{R2.25_i} + C_{R3.75_i}}{2} - C_{R3.00_i} \right)$$

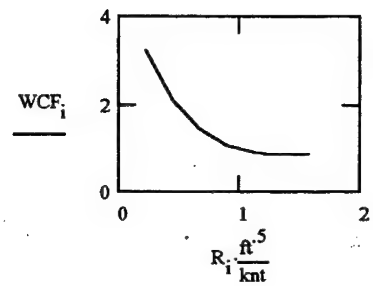
$$C_{RTSS} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0.001 \\ 0.002 \\ 0.004 \\ 0.004 \end{bmatrix} \qquad R_{RTSS_i} := .5 \cdot \left[\rho_{SW} \cdot S_S \cdot (V_i)^2 \cdot C_{RTSS_i} \right] \qquad R_{RTSS} = \begin{bmatrix} 765.82 \\ 3063.279 \\ 7918.902 \\ 31346.623 \\ 89035.271 \\ 200574.47 \\ 418973.994 \end{bmatrix} \cdot lbf$$

III2 Calculate Bare Hull Ship Resistance - Worm Curve data from ASSET:

$$WCFA := \begin{bmatrix} .2 & 3.5 \\ .3 & 2.95 \\ .4 & 2.5 \\ .5 & 2.1 \\ .6 & 1.8 \\ .7 & 1.55 \\ .8 & 1.33 \\ .9 & 1.17 \\ 1.0 & 1.07 \\ 1.1 & 1 \\ 1.2 & .94 \\ 1.3 & .89 \\ 1.4 & .88 \\ 1.5 & .87 \\ 1.6 & .87 \end{bmatrix}$$

$$iw := 1 .. 15$$

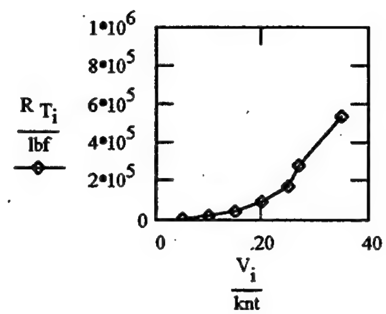
$$R = \begin{bmatrix} 0.225 \\ 0.449 \\ 0.674 \\ 0.899 \\ 1.123 \\ 1.213 \\ 1.573 \end{bmatrix} \cdot \frac{knt}{ft^{.5}} \qquad WCF := \begin{bmatrix} 3.242 \\ 2.124 \\ 1.460 \\ 1.083 \\ .923 \\ .880 \\ .870 \end{bmatrix}$$



$$R_{R_i} := R_{RTSS_i} \cdot WCF_i$$

$$R_{T_i} := R_{F_i} + R_{R_i}$$

$$R_R = \begin{bmatrix} 2482.788 \\ 6506.404 \\ 11561.597 \\ 33948.392 \\ 82179.556 \\ 176505.533 \\ 364507.375 \end{bmatrix} \cdot lbf \qquad R_T = \begin{bmatrix} 6881.321 \\ 22915.697 \\ 47080.19 \\ 95434.858 \\ 176335.081 \\ 285578.054 \\ 543664.612 \end{bmatrix} \cdot lbf$$



III3. Total Ship Effective Horsepower:

hull: $$P_{EBH_i} := R_{T_i} \cdot V_i \qquad \frac{P_{EBH}}{hp} = \begin{bmatrix} 105.722 \\ 704.137 \\ 2169.969 \\ 5864.906 \\ 13545.74 \\ 23692.594 \\ 58468.658 \end{bmatrix}$$

$$C_{SD} := .28$$

appendage: $P_{EAPP_i} := \left(LWL \cdot D_P \cdot C_{DAPP} + .5 \cdot C_{SD} \cdot \rho_{SW} \cdot A_{SD}\right) \cdot \left(V_i\right)^3$

$$\frac{P_{EAPP}}{hp} = \begin{bmatrix} 95.946 \\ 767.565 \\ 2590.531 \\ 6140.518 \\ 11993.199 \\ 15107.977 \\ 32909.338 \end{bmatrix}$$

air: $P_{EAA_i} := .5 \cdot C_{AA} \cdot A_W \cdot \rho_A \cdot \left(V_i\right)^3$

$$\frac{P_{EAA}}{hp} = \begin{bmatrix} 2.583 \\ 20.667 \\ 69.75 \\ 165.334 \\ 322.918 \\ 406.784 \\ 886.088 \end{bmatrix}$$

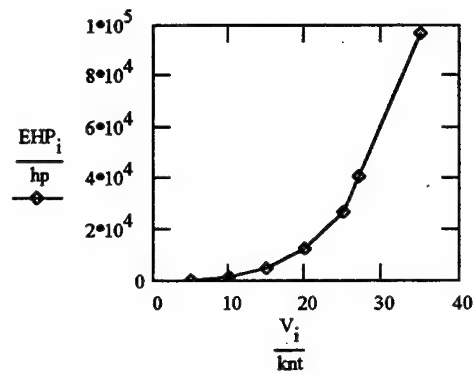
$$P_{ET_i} := P_{EBH_i} + P_{EAPP_i} + P_{EAA_i}$$

$$\frac{P_{ET}}{hp} = \begin{bmatrix} 204.251 \\ 1492.368 \\ 4830.25 \\ 12170.758 \\ 25861.858 \\ 39207.355 \\ 92264.084 \end{bmatrix}$$

$$EHP_i := PMF \cdot P_{ET_i}$$

$\frac{V_i}{knt}$
5
10
15
20
25
27
35

$$EHP = \begin{bmatrix} 214.464 \\ 1566.987 \\ 5071.763 \\ 12779.296 \\ 27154.951 \\ 41167.722 \\ 96877.288 \end{bmatrix} \cdot hp$$

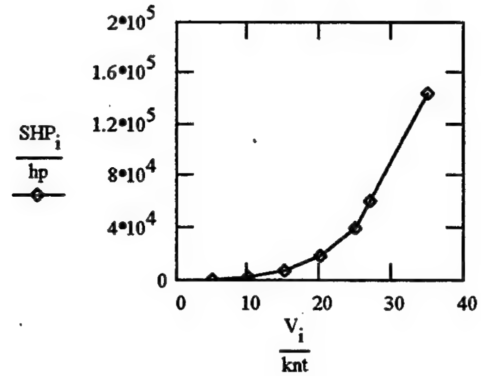


i

III4. Shaft Horsepower:

Approximate Propulsive Coeficient (PC): $PC := .67$ $SHP_i := \frac{EHP_i}{PC}$

$$SHP = \begin{bmatrix} 320.095 \\ 2338.786 \\ 7569.795 \\ 19073.576 \\ 40529.777 \\ 61444.362 \\ 144592.967 \end{bmatrix} \cdot hp$$



Endurance Shaft Horsepower: $P_e := SHP_4$ $P_e = 19073.576 \cdot hp$

Sustained Speed Installed Shaft Horsepower Required (Allows for fouling and sea state):

$P_S := SHP_6$ $P_S = 61444.362 \cdot hp$ $P_{IREQ} := 1.25 \cdot P_S$ $P_{IREQ} = 76805.452 \cdot hp$

Actual installed SHP must be greater than P_{IREQ}

$P_{IBRAKE} := N_{PENG} \cdot P_{BPENG}$ $P_{IBRAKE} = 105800 \cdot hp$ $\eta := .97$ $P_I := \eta \cdot P_{IBRAKE}$ $P_I = 102626 \cdot hp$

(P_I must be > P_{IREQ}) $P_{IREQ} = 76805.452 \cdot hp$ $ERR_{POWER} := \frac{P_I - P_{IREQ}}{P_{IREQ}}$ $ERR_{POWER} = 0.336$

III5. Estimate Propulsion Fuel Required:
Reference: DDS 200-1 "Calculate of Surface Ship Endurance Fuel"

Average Endurance Brake SHP Required (Allows for fouling and sea state):

$$P_{eBAVG} := 1.1 \cdot \frac{P_e}{\eta} \qquad P_{eBAVG} = 21629.828 \cdot hp$$

Specific fuel rate for propulsion engines:
(GT; FR for diesel = .327)

$FR := 1.97 \cdot \frac{lb}{hp^{.85} \cdot hr} \cdot P_{eBAVG}^{-.15}$ $FR = 0.441 \cdot \frac{lb}{hp \cdot hr}$

(for ICR: FR=.347 lb/hphr)

Margin for instrumentation and machinery differences, f(P_e/P_I): $f_1 := 1.04$

Specified fuel rate: $FR_{SP} := f_1 \cdot FR$

Average fuel rate allowing for plant deterioration:

$$FR_{AVG} := 1.05 \cdot FR_{SP} \qquad FR_{AVG} = 0.481 \cdot \frac{lb}{hp \cdot hr}$$

Burnable propulsion endurance fuel weight:

$$W_{BP} := \frac{E}{V_e} \cdot \left(P_{eBAVG} \cdot FR_{AVG}\right) \qquad W_{BP} = 1742.879 \cdot lton$$

Tailpipe allowance and propulsion endurance fuel: $TPA := .95$
(shallow tanks)

$$W_{FP} := \frac{W_{BP}}{TPA} \qquad W_{FP} = 1834.609 \cdot lton$$

Allow for expansion and tank structure in required propulsion tank volume:

$$\gamma_F := 43 \cdot \frac{ft^3}{lton} \qquad V_{FP} := 1.02 \cdot 1.05 \cdot \gamma_F \cdot W_{FP} \qquad V_{FP} = 84489.268 \cdot ft^3$$

III6. Estimate electric load.

Reference: DDS 310-1

Estimate Maximum Functional Load based on parametrics for WINTER cruise condition:

Propulsion: $kW_P := .00466 \cdot \frac{kW}{hp} \cdot P_{IBRAKE}$ $\qquad kW_P = 493.028 \cdot kW$

Steering: $kW_S := .00583 \cdot \frac{kW}{ft^2} \cdot LWL \cdot T$ $\qquad kW_S = 48.779 \cdot kW$

Lighting: $kW_L := .0002053 \cdot \frac{kW}{ft^3} \cdot 1.8 \cdot LWL \cdot T \cdot B$ $\qquad kW_L = 172.357 \cdot kW$

Miscellaneous: $kW_M := 46.1 \cdot kW$

Heating: $kW_H := .0013 \cdot \frac{kW}{ft^3} \cdot 1.25 \cdot LWL \cdot T \cdot B$ $\qquad kW_H = 757.917 \cdot kW$

Ventilation: $kW_{CPS} := .00026 \cdot \frac{kW}{ft^3} \cdot 1.8 \cdot LWL \cdot T \cdot B$ **(zero if no CPS)** $\qquad kW_{CPS} = 218.28 \cdot kW$

$kW_V := .19 \cdot (kW_H + kW_P) + kW_{CPS}$ $\qquad kW_V = 455.96 \cdot kW$

Air Conditioning: $kW_{AC} := .67 \cdot \left(.1 \cdot kW \cdot N_T + .0015 \cdot \frac{kW}{ft^3} \cdot .47 \cdot 1.3 \cdot LWL \cdot T \cdot B + .1 \cdot kW_P \right)$

$kW_{AC} = 329.485 \cdot kW$

Aux Boiler and FW:
(electric boiler) $kW_B := .94 \cdot N_T \cdot kW$ $\qquad kW_B = 141 \cdot kW$

Firemain: $kW_F := .0001 \cdot \frac{kW}{ft^3} \cdot 1.8 \cdot LWL \cdot T \cdot B$ $\qquad kW_F = 83.954 \cdot kW$

Unrep and handling: $kW_{RH} := .00002 \cdot \frac{kW}{ft^3} \cdot 1.25 \cdot LWL \cdot T \cdot B$ $\qquad kW_{RH} = 11.66 \cdot kW$

Aux Machinery: $kW_A := .22 \cdot N_T \cdot kW + kW_{fins}$ $kW_A = 33 \cdot kW$

Services and Work Spaces: $kW_{SERV} := .35 \cdot N_T \cdot kW$ $kW_{SERV} = 52.5 \cdot kW$

Non-Payload Functional Load:

$$kW_{NP} := kW_P + kW_S + kW_L + kW_M + kW_H + kW_V + kW_{AC} + kW_B + kW_F + kW_{RH} + kW_A + kW_{SER}$$

Maximum Functional Load:

$kW_{MFL} := kW_{PAY} + kW_{NP}$ $kW_{MFL} = 3165.811 \cdot kW$

MFL with margins: (design,growth):

$kW_{MFLM} := 1.2 \cdot 1.2 \cdot kW_{MFL}$ $kW_{MFLM} = 4558.767 \cdot kW$

Installed Electrical Power Required:

Power available per generator: $kW_G = 3000 \cdot kW$

Power required per generator: $kW_{GREQ} := \dfrac{kW_{MFLM}}{(N_G - 1) \cdot .9}$ $kW_{GREQ} = 2532.648 \cdot kW$

$$ERR_{KW} := \frac{kW_G - kW_{GREQ}}{kW_{GREQ}}$$

24 hour electrical load:

$kW_{24} := .5 \cdot (kW_{MFL} - kW_P - kW_S) + .8 \cdot (kW_P + kW_S)$ $kW_{24} = 1745.447 \cdot kW$

$ERR_{KW} = 0.185$

with margin (design): $kW_{24AVG} := 1.2 \cdot kW_{24}$ $kW_{24AVG} = 2094.537 \cdot kW$

III7. Estimate Electric Fuel Rate: $FR_G = 0.113 \cdot \dfrac{lb}{kW \cdot hr}$

Margin for instrumentation and machinery differences, f(P_e/P_l): $f_{1e} := 1.04$

Specified fuel rate: $FR_{GSP} := f_{1e} \cdot FR_G$

Average fuel rate allowing for plant deterioration:

$FR_{GAVG} := 1.05 \cdot FR_{GSP}$ $FR_{GAVG} = 0.124 \cdot \dfrac{lb}{kW \cdot hr}$ $FR_{GAVG} = 0.092 \cdot \dfrac{lb}{hp \cdot hr}$

III8. Estimate Electrical and Total fuel Required

Burnable electrical endurance fuel weight:

$W_{Be} := \dfrac{E}{V_e} \cdot (kW_{24AVG} \cdot FR_{GAVG})$ $W_{Be} = 43.416 \cdot lton$

Tailpipe allowance and electrical endurance fuel:

TPA := .95

(shallow tanks)

$$W_{Fe} := \frac{W_{Be}}{TPA} \qquad W_{Fe} = 45.701 \cdot lton$$

Allow for expansion and tank structure in required electrical fuel tank volume:

$$V_{Fe} := 1.02 \cdot 1.05 \cdot \gamma_F \cdot W_{Fe} \qquad V_{Fe} = 2104.684 \cdot ft^3$$

Total ship fuel: (DFM)

$$W_{F41} := W_{FP} + W_{Fe} \qquad W_{F41} = 1880.311 \cdot lton$$

$$V_F := V_{FP} + V_{Fe} \qquad V_F = 86593.952 \cdot ft^3$$

IV. Space Estimate

IVA. Available Space

IVA1. Underwater Hull Volume Available

$$V_{HUW} := V_{FL} \qquad V_{HUW} = 233905 \cdot ft^3$$

IVA2. Sheer Line. (3 criteria)

1) Keep deck edge above water at 25 degree heel

2) Longitudinal strength

3) Contain machinery box height: $H_{MBMIN} = 22 \cdot ft$

$$M := \begin{bmatrix} .21 \cdot B + T \\ \dfrac{LWL}{15} \\ H_{MBMIN} \end{bmatrix} \qquad M = \begin{bmatrix} 28.599 \\ 33.02 \\ 22 \end{bmatrix} \cdot ft \qquad D_{10MIN} := \max(M) \qquad D_{10MIN} = 33.02 \cdot ft$$

$$D_{10} := D_{10MIN} + 1 \cdot ft \qquad D_{10} = 34.02 \cdot ft$$

$$D_{0MIN} := 1.011827 \cdot T - 6.36215 \cdot \frac{10^{-6}}{ft} \cdot LWL^2 + 2.780649 \cdot 10^{-2} \cdot LWL + T \qquad D_{0MIN} = 46.196 \cdot ft \qquad D_0 := D_{0MIN}$$

$$D_{20MIN} := .014 \cdot LWL \cdot \left(2.125 + 1.25 \cdot \frac{10^{-3}}{ft} \cdot LWL\right) + T \qquad D_{20MIN} = 35.921 \cdot ft \qquad D_{20} := D_{20MIN}$$

IVA3. Above-Water Hull Volume

$$F_0 := D_0 - T \qquad F_{10} := D_{10} - T \qquad F_{20} := D_{20} - T$$

$$A_{PRO} := LWL \cdot \frac{F_0 + 4 \cdot F_{10} + F_{20}}{6} \qquad F_{AV} := \frac{A_{PRO}}{LWL} \qquad F_{AV} = 19.474 \cdot ft$$

$$D_{AV} := F_{AV} + T \qquad D_{AV} = 36.366 \cdot ft$$

cubic #: $CN := \dfrac{LWL \cdot B \cdot D_{AV}}{10^5 \cdot ft^3} \qquad CN = 10.041$

$$C_W := .236 + .836 \cdot C_P \qquad C_W = 0.729$$

flare factor: $f_f := .714599 + .18098 \cdot \frac{D_{AV}}{T} - .018828 \cdot \left(\frac{D_{AV}}{T}\right)^2$ $M_f := \begin{bmatrix} f_f \\ 1 \end{bmatrix}$ $f_f := \max(M_f)$

$f_f = 1.017$

$V_{HAW} := LWL \cdot B \cdot F_{AV} \cdot C_W \cdot f_f$ $V_{HAW} = 398749.111 \cdot ft^3$

IVA4. Total Hull Volume.

$V_{HT} := V_{HUW} + V_{HAW}$ $V_{HT} = 632654.111 \cdot ft^3$

IVA5. Size Deck House:

$V_{DMAX} := .0025 \cdot LWL^3$ $V_{DMAX} = 303772.727 \cdot ft^3$

$V_{DMIN} := .0005 \cdot LWL^3$ $V_{DMIN} = 60754.545 \cdot ft^3$ $V_D = 97715 \cdot ft^3$

IVA6. Calculate Total Ship Volume

$V_T := V_{HT} + V_D$ $V_T = 730369.111 \cdot ft^3$

IVB. Space Requirement

IVB1. Machinery Box **(assumed near midships)** $B_{MB} := B$ $B_{MB} = 55.745 \cdot ft$

$H_{MB} := D_{10}$ $L_{MB} = 40 \cdot ft$ $A_{MB} := B \cdot T \cdot C_X + B \cdot (H_{MB} - T)$ $A_{MB} = 1755.202 \cdot ft^2$

Calculate Machinery Box Volume:

$V_{MB} := L_{MB} \cdot A_{MB} \cdot C_{PMB}$ $V_{MB} = 70067.665 \cdot ft^3$ $V_{AUX} := 1.2 \cdot V_{MB}$ $V_{AUX} = 84081.198 \cdot ft^3$

IVB2. Tankage

Helo:

Helo fuel weight from Payload Spreadsheet: $W_{F42} = 63.8 \cdot lton$

Allow for tank structure and expansion: $\gamma_{HF} := 43 \cdot \frac{ft^3}{lton}$

$V_{HF} := 1.02 \cdot 1.05 \cdot W_{F42} \cdot \gamma_{HF}$ $V_{HF} = 2938.181 \cdot ft^3$

Lube Oil:

LO weight: $W_{F46} := 7.2 \cdot lton$

Allow for tank structure and expansion: $\gamma_{LO} := 39 \cdot \frac{ft^3}{lton}$

$V_{LO} := 1.02 \cdot 1.05 \cdot W_{F46} \cdot \gamma_{LO}$ $V_{LO} = 300.737 \cdot ft^3$

Potable Water:

Water weight: $W_{F52} := N_T \cdot .15 \cdot lton$ $W_{F52} = 22.5 \cdot lton$

Allow for tank structure: $\gamma_W := 36 \cdot \frac{ft^3}{lton}$

$V_W := 1.02 \cdot W_{F52} \cdot \gamma_W$ $V_W = 826.2 \cdot ft^3$

Sewage: $V_{SEW} := N_T \cdot 2 \cdot ft^3$ $\quad V_{SEW} = 300 \cdot ft^3$

Waste Oil: $V_{WASTE} := .005 \cdot V_{FL}$ $\quad V_{WASTE} = 1169.525 \cdot ft^3$

Clean Balast: $V_{BAL} := .032 \cdot V_{FL}$ $\quad V_{BAL} := 0 \cdot ft^3$ $\quad V_{BAL} = 0 \cdot ft^3$

(for compensated system)

Total:

$$V_{TK} := V_F + V_{HF} + V_{LO} + V_W + V_{SEW} + V_{WASTE} + V_{BAL} \qquad V_{TK} = 92128.595 \cdot ft^3$$

IVB3. Payload Deck Areas

Deckhouse payload area: (including access) $A_{DPR} := 1.15 \cdot A_{DPA} + 1.23 \cdot A_{DPC}$ $\quad A_{DPR} = 10143.981 \cdot ft^2$

Hull payload area: (including access) $A_{HPR} := 1.15 \cdot A_{HPA} + 1.23 \cdot A_{HPC}$ $\quad A_{HPR} = 9797.796 \cdot ft^2$

IVB4. Living Deck Area

Deckhouse: $A_{COXO} := 225 \cdot ft^2$ $\quad A_{DO} := 75 \cdot N_O \cdot ft^2$ $\quad A_{DO} = 1125 \cdot ft^2$

$A_{DL} := A_{COXO} + A_{DO}$ $\quad A_{DL} = 1350 \cdot ft^2$

Hull: $A_{HAB} := 50 \cdot ft^2$ $\quad A_{HL} := \left(A_{HAB} + \frac{LWL}{100} \cdot ft\right) \cdot N_T - A_{DL}$

$A_{HL} = 6892.952 \cdot ft^2$

IVB5. Hull Stores

$$A_{HS} := 300 \cdot ft^2 + .0158 \cdot \frac{ft^2}{lb} \cdot N_T \cdot 9 \cdot \frac{lb}{day} \cdot T_S \qquad A_{HS} = 1259.85 \cdot ft^2$$

IVB6. Other Ship Functions

Deckhouse:

Maintenance:

$A_{DM} := .05 \cdot \left(A_{DPR} + A_{DL}\right)$ $\quad A_{DM} = 574.699 \cdot ft^2$

Bridge and Chartroom:

$A_{DB} := 16 \cdot ft \cdot (B - 18 \cdot ft)$ $\quad A_{DB} = 603.921 \cdot ft^2$

Engine Inlet/Exhaust:

$A_{DIE} := 1.4 \cdot N_{DIE} \cdot \left(A_{PIE} + A_{eIE}\right)$ $\quad A_{DIE} = 918.4 \cdot ft^2$

Hull:

Ship Functions:

$A_{HSF} := 2500 \cdot ft^2 \cdot CN$ $\quad A_{HSF} = 25102.384 \cdot ft^2$

Engine Inlet/Exhaust:

$$A_{HIE} := 1.4 \cdot \left(N_{HPIE} \cdot A_{PIE} + N_{HeIE} \cdot A_{eIE}\right) \qquad A_{HIE} = 161.28 \cdot ft^2$$

IVB7. Total Required Area and Volume

Hull:

$$A_{HR} := A_{HPR} + A_{HL} + A_{HS} + A_{HSF} + A_{HIE} \qquad A_{HR} = 43214.262 \cdot ft^2$$

$$V_{HR} := H_{DK} \cdot A_{HR} \qquad V_{HR} = 388928.354 \cdot ft^3$$

Deckhouse:

$$A_{DR} := A_{DPR} + A_{DL} + A_{DM} + A_{DB} + A_{DIE} \qquad A_{DR} = 13591.001 \cdot ft^2$$

$$V_{DR} := H_{DK} \cdot A_{DR} \qquad V_{DR} = 122319.01 \cdot ft^3$$

Total:

$$A_{TR} := A_{HR} + A_{DR} \qquad A_{TR} = 56805.263 \cdot ft^2$$

$$V_{TR} := H_{DK} \cdot A_{TR} \qquad V_{TR} = 511247.364 \cdot ft^3$$

IVC. Space Balance

$$V_D = 97715 \cdot ft^3 \qquad V_{DR} = 122319.01 \cdot ft^3$$

$$V_{HA} := V_{HT} - V_{MB} - V_{AUX} - V_{TK} \qquad V_{HA} = 386376.654 \cdot ft^3 \qquad V_{HR} = 388928.354 \cdot ft^3$$

$$V_{TA} := V_{HA} + V_D \qquad V_{TA} = 484091.654 \cdot ft^3 \quad > \quad V_{TR} = 511247.364 \cdot ft^3$$

$$A_{HA} := \frac{V_{HA}}{H_{DK}} \qquad A_{HA} = 42930.739 \cdot ft^2 \qquad A_{HR} = 43214.262 \cdot ft^2$$

$$A_{DA} := \frac{V_D}{H_{DK}} \qquad A_{DA} = 10857.222 \cdot ft^2 \qquad A_{DR} = 13591.001 \cdot ft^2$$

$$A_{TA} := A_{DA} + A_{HA} \qquad A_{TA} = 53787.962 \cdot ft^2 \quad > \quad A_{TR} = 56805.263 \cdot ft^2$$

$$ERR_{VOL} := \frac{V_{TA} - V_{TR}}{V_{TR}} \quad ERR_{VOL} = -0.053117 \qquad ERR_{AREA} := \frac{A_{TA} - A_{TR}}{A_{TR}} \quad ERR_{AREA} = -0.053117$$

V. Weight

V1. Propulsion (200)

Basic Machinery:
(230+241/242+
250-290)

$$W_{BM} := P_I \cdot \frac{lb}{hp} \cdot \left[9.0 + 12.4 \cdot \left(P_I \cdot \frac{10^{-5}}{hp} - 1\right)^2\right] \qquad W_{BM} = 412.728 \cdot lton$$

Shafting: $f_S := .5$ $\quad W_S := .356 \cdot \frac{\text{lton}}{\text{ft}} \cdot LWL \cdot f_S \qquad W_S = 88.164 \cdot \text{lton}$
(243)

(f_S=0.5 for twin screws, 0.33 for single screw)

Props:
(245)

$$W_{PR} := .05575 \cdot \text{lb} \cdot \left(\frac{D_P}{\text{ft}}\right)^{5.497 - \frac{.0433}{\text{ft}} \cdot D_P} \cdot N_P \qquad W_{PR} = 36.613 \cdot \text{lton}$$

Bearings:
(244)

$$W_B := .15 \cdot \left(W_S + W_{PR}\right) \qquad W_B = 18.717 \cdot \text{lton}$$

Total Shafting: $\quad W_{ST} := W_S + W_B + W_{PR} \qquad W_{ST} = 143.493 \cdot \text{lton}$

Total Propulsion: $\quad W_2 := W_{BM} + W_{ST} + W_{237} \qquad W_2 = 556.222 \cdot \text{lton}$

V2. Electrical Plant (300)

$$W_3 := 50 \cdot \text{lton} + .03214 \cdot \frac{\text{lton}}{\text{kW}} \cdot N_G \cdot kW_G \qquad W_3 = 339.26 \cdot \text{lton}$$

V3. Command/Control/Surveillance (400)

Gyro/IC/Navigation (420, 430): $\quad W_{IC} := 4.65 \cdot CN \cdot \text{lton} \qquad W_{IC} = 46.69 \cdot \text{lton}$

Other/Misc Group 400: $\quad W_{CO} := 2.24 \cdot CN \cdot \text{lton} \qquad W_{CO} = 22.492 \cdot \text{lton}$

Cabling: $\quad W_{CC} := .04 \cdot \left(W_{P400} + W_{IC} + W_{CO}\right) \qquad W_{CC} = 8.693 \cdot \text{lton}$

$$W_4 := W_{P400} + W_{IC} + W_{CO} + W_{CC} + W_{498} \qquad W_4 = 313.915 \cdot \text{lton}$$

V4. Auxiliary Systems (500)

aux steam (electric aux boiler): **hotel steam:** $Q_{HS} := 15 \cdot N_T$ **distiller:** $Q_{DS} := 6.5 \cdot N_T + 250$

$W_{517} := .0013 \cdot \left(Q_{HS} + Q_{DS}\right) \cdot \text{lton} \qquad W_{517} = 4.518 \cdot \text{lton}$ **aux sys operating fluids:** $W_{598} := .000075 \cdot V_T \cdot \frac{\text{lton}}{\text{ft}^3}$

$W_{598} = 54.778 \cdot \text{lton}$

$$W_{AUX} := \left[.000772 \cdot \left(\frac{V_T}{\text{ft}^3}\right)^{1.443} + 5.14 \cdot \frac{V_T}{\text{ft}^3} + 6.19 \cdot \left(\frac{V_T}{\text{ft}^3}\right)^{.7224} + 377 \cdot N_T + 2.74 \cdot \frac{P_I}{\text{hp}}\right] \cdot 10^{-4} \cdot \text{lton} + 113.8 \cdot \text{lton}$$

environmental support: $\quad W_{593} := 10 \cdot \text{lton} \qquad W_5 := W_{P500} + W_{517} + W_{593} + W_{CPS} \qquad W_5 = 91.907 \cdot \text{lton}$

V5. Outfit & Furnishings (600)

Hull Fittings: $W_{OFH} := \left(31.4 + \frac{.0003187}{ft^3} \cdot V_T\right) \cdot lton$ $\quad W_{OFH} = 264.169 \cdot lton$

Personnel-related: $W_{OFP} := .8 \cdot (N_T - 9.5) \cdot lton$ $\quad W_{OFP} = 112.4 \cdot lton$

$W_6 := W_{OFP} + W_{P600}$ $\quad W_6 = 120.14 \cdot lton$

V6. Structure (100)

Hull (110-140, 160, 190): $W_{BH} := C_{HMAT} \cdot \left(1.68341 \cdot CN^2 + 167.1721 \cdot CN - 103.283\right) \cdot lton$ $\quad W_{BH} = 1622.856 \cdot lton$

$\rho_{DH} := \mathrm{if}\left(C_{DHMAT} = 1, .0007, .001429\right)$ $\quad \rho_{DH} = 0.001$

Deckhouse (150): $W_{DH} := \rho_{DH} \cdot \frac{lton}{ft^3} \cdot V_D$ $\quad W_{DH} = 139.635 \cdot lton$

Masts: $W_{171} := .0688 \cdot \frac{lton}{ft} \cdot LWL - 13.75 \cdot lton$ $\quad W_{171} = 20.327 \cdot lton$

Foundations: $W_{180} := .0675 \cdot W_{BM} + .072 \cdot \left(W_3 + W_4 + W_5 + W_7\right)$ $\quad W_{180} = 89.956 \cdot lton$

$W_1 := W_{BH} + W_{DH} + W_{171} + W_{180} + W_{165} + W_{164}$ $\quad W_1 = 1958.474 \cdot lton$

V7. Single Digit Weight Summary & Weight Balance: $\quad i1 := 1, 2 .. 7$

Weight margin: (Future Growth) $W_{M24} := .1 \cdot \left(\sum_{i1} W_{i1}\right)$ $\quad W_{M24} = 349.729 \cdot lton$

Lightship:

$W_{LS} := \sum_{i1} W_{i1} + W_{M24}$ $\quad W_{LS} = 3847.017 \cdot lton$

Additional Loads:

Provisions: $W_{F31} := N_T \cdot 9 \cdot \frac{lb}{day} \cdot T_S$ $\quad W_{F31} = 27.121 \cdot lton$

General stores: $W_{F32} := .0009598 \cdot \frac{lton}{day} \cdot T_S \cdot N_T$ $\quad W_{F32} = 6.479 \cdot lton$

Crew: $W_{F10} := 236 \cdot lb \cdot N_E + 400 \cdot lb \cdot \left(N_O + 1\right)$ $\quad W_{F10} = 17.08 \cdot lton$

$W_T := W_{LS} + W_{F41} + W_{F42} + W_{F20} + W_{F46} + W_{F52} + W_{F31} + W_{F32} + W_{F10}$

$W_T = 6058.967 \cdot lton$

Weight Balance: $ERR_{WEIGHT} := \frac{\Delta_{FL} - W_T}{W_T}$ $\quad ERR_{WEIGHT} = 0.102993$

Weights Independent of the Design Variables:

$$W_{IND} := W_{237} + W_3 + W_5 + W_6 + W_7 + W_{165} + W_{164} + W_{F31} + W_{F32} + W_{F10} + W_{F20}$$

$$W_{IND} = 992.517 \cdot \text{lton}$$

VI. Stability

VI1. Calculate Light Ship Weight Group Moments:

Weight	**VCG**		**Product**
$W_{BH} = 1622.856 \cdot \text{lton}$	$VCG_1 := .527 \cdot D_{10}$	$VCG_1 = 17.929 \cdot \text{ft}$	$P_1 := W_{BH} \cdot VCG_1$
$W_{DH} = 139.635 \cdot \text{lton}$	$VCG_2 := D_{10} + 1.5 \cdot H_{DK}$	$VCG_2 = 47.52 \cdot \text{ft}$	$P_2 := W_{DH} \cdot VCG_2$
$W_{180} = 89.956 \cdot \text{lton}$	$VCG_3 := .68 \cdot D_{10}$	$VCG_3 = 23.134 \cdot \text{ft}$	$P_3 := W_{180} \cdot VCG_3$
$W_{171} = 20.327 \cdot \text{lton}$	$VCG_4 := 2.65 \cdot D_{10}$	$VCG_4 = 90.153 \cdot \text{ft}$	$P_4 := W_{171} \cdot VCG_4$

$$P_{100} := P_1 + P_2 + P_3 + P_4 \qquad VCG_{100} := \frac{P_{100}}{W_1} \qquad VCG_{100} = 20.243 \cdot \text{ft}$$

$W_{BM} = 412.728 \cdot \text{lton}$	$VCG_5 := .5 \cdot D_{10}$	$VCG_5 = 17.01 \cdot \text{ft}$	$P_5 := W_{BM} \cdot VCG_5$
$W_{ST} = 143.493 \cdot \text{lton}$	$VCG_6 := 3.9 \cdot \text{ft} + .19 \cdot T$	$VCG_6 = 7.11 \cdot \text{ft}$	$P_6 := W_{ST} \cdot VCG_6$
$W_{237} = 0 \cdot \text{lton}$	$VCG_7 := VCG_{237}$	$VCG_7 = 0 \cdot \text{ft}$	$P_7 := W_{237} \cdot VCG_7$

$$P_{200} := P_5 + P_6 + P_7 \qquad VCG_{200} := \frac{P_{200}}{W_2} \qquad VCG_{200} = 14.456 \cdot \text{ft}$$

$W_3 = 339.26 \cdot \text{lton}$	$VCG_8 := .65 \cdot D_{10}$	$VCG_8 = 22.113 \cdot \text{ft}$	$P_8 := W_3 \cdot VCG_8$
$W_{IC} = 46.69 \cdot \text{lton}$	$VCG_9 := D_{10}$	$VCG_9 = 34.02 \cdot \text{ft}$	$P_9 := W_{IC} \cdot VCG_9$
$W_{CO} = 22.492 \cdot \text{lton}$	$VCG_{10} := 5.6 \cdot \text{ft} + .4625 \cdot D_{10}$	$VCG_{10} = 21.334 \cdot \text{ft}$	$P_{10} := W_{CO} \cdot VCG_{10}$
$W_{CC} = 8.693 \cdot \text{lton}$	$VCG_{11} := .5 \cdot D_{10}$	$VCG_{11} = 17.01 \cdot \text{ft}$	$P_{11} := W_{CC} \cdot VCG_{11}$
$W_{498} = 87.9 \cdot \text{lton}$	$VCG_{12} := VCG_{498}$	$VCG_{12} = -1.2 \cdot \text{ft}$	$P_{12} := W_{498} \cdot VCG_{12}$
$W_{AUX} = 555.959 \cdot \text{lton}$	$VCG_{13} := .9 \cdot (D_{10} - 7.4 \cdot \text{ft})$	$VCG_{13} = 23.958 \cdot \text{ft}$	$P_{13} := W_{AUX} \cdot VCG_{13}$
$W_{517} = 4.518 \cdot \text{lton}$	$VCG_{14} := .5 \cdot H_{MB}$	$VCG_{14} = 17.01 \cdot \text{ft}$	$P_{14} := W_{517} \cdot VCG_{14}$
$W_{OFH} = 264.169 \cdot \text{lton}$	$VCG_{15} := .805 \cdot D_{10}$	$VCG_{15} = 27.386 \cdot \text{ft}$	$P_{15} := W_{OFH} \cdot VCG_{15}$
$W_{OFP} = 112.4 \cdot \text{lton}$	$VCG_{16} := 8 \cdot \text{ft} + .71 \cdot D_{10}$	$VCG_{16} = 32.154 \cdot \text{ft}$	$P_{16} := W_{OFP} \cdot VCG_{16}$

$ip := 1..16$

$$P_{WG} := \sum_{ip} P_{ip} + W_P \cdot VCG_P - W_{VP} \cdot VCG_{VP} \qquad P_{WG} = 90665.675 \cdot lton \cdot ft$$

V!2. Light Ship KG

$$VCG_{LS} := \frac{P_{WG}}{\sum_{i1} W_{i1}} \qquad VCG_{LS} = 25.925 \cdot ft \qquad KG_{LS} := VCG_{LS} \qquad KG_{LS} = 25.925 \cdot ft$$

VI3. Calculate Variable Load Weight Group Moments:

Weight	VCG		Product
$W_{F10} = 17.08 \cdot lton$	$VCG_{17} := .746 \cdot D_{10}$	$VCG_{17} = 25.379 \cdot ft$	$P_{17} := W_{F10} \cdot VCG_{17}$
$W_{F31} = 27.121 \cdot lton$	$VCG_{18} := .55 \cdot D_{10}$	$VCG_{18} = 18.711 \cdot ft$	$P_{18} := W_{F31} \cdot VCG_{18}$
$W_{F32} = 6.479 \cdot lton$	$VCG_{19} := .65 \cdot D_{10}$	$VCG_{19} = 22.113 \cdot ft$	$P_{19} := W_{F32} \cdot VCG_{19}$
$W_{F41} = 1880.311 \cdot lton$	$VCG_{20} := 7.5 \cdot ft$	$VCG_{20} = 7.5 \cdot ft$	$P_{20} := W_{F41} \cdot VCG_{20}$
$W_{F42} = 63.8 \cdot lton$	$VCG_{21} := 10. \cdot ft$	$VCG_{21} = 10 \cdot ft$	$P_{21} := W_{F42} \cdot VCG_{21}$
$W_{F46} = 7.2 \cdot lton$	$VCG_{22} := .35 \cdot D_{10}$	$VCG_{22} = 11.907 \cdot ft$	$P_{22} := W_{F46} \cdot VCG_{22}$
$W_{F52} = 22.5 \cdot lton$	$VCG_{23} := 7.5 \cdot ft$	$VCG_{23} = 7.5 \cdot ft$	$P_{23} := W_{F52} \cdot VCG_{23}$

$$iL := 17..23 \qquad P_{WGL} := \sum_{iL} P_{iL} + W_{VP} \cdot VCG_{VP} \qquad P_{WGL} = 23519.564 \cdot lton \cdot ft$$

$$W_L := W_{F41} + W_{F42} + W_{F20} + W_{F46} + W_{F52} + W_{F31} + W_{F32} + W_{F10} \qquad W_L = 2211.95 \cdot lton$$

$$VCG_L := \frac{P_{WGL}}{W_L} \qquad VCG_L = 10.633 \cdot ft$$

VI4. Calculate Ship Stability Characteristics:

$$KG_{MARG} := .5 \cdot ft \qquad KG := \frac{W_{LS} \cdot KG_{LS} + W_L \cdot VCG_L}{W_T} + KG_{MARG} \qquad C_{IT} := -.497 + 1.44 \cdot C_W \qquad C_{IT} = 0.553$$

$$KB := \frac{T}{3} \cdot \left(2.5 - \frac{C_P \cdot C_X}{C_W}\right) \qquad BM := \frac{LWL \cdot B^3 \cdot C_{IT}}{12 \cdot V_{FL}} \qquad GM := KB + BM - KG \qquad C_{GMB} := \frac{GM}{B}$$

$$KG = 20.842 \cdot ft \qquad KB = 10.205 \cdot ft \qquad BM = 16.907 \cdot ft \qquad GM = 6.27 \cdot ft \qquad C_{GMB} = 0.112$$

$\mathrm{Mdol} := \mathrm{coul}$ $\qquad \mathrm{Kdol} := \dfrac{\mathrm{Mdol}}{1000}$

$\mathrm{Bdol} := 1000 \cdot \mathrm{Mdol}$ $\qquad \mathrm{dol} := \dfrac{\mathrm{Kdol}}{1000}$

VII. VERY SIMPLIFIED COST MODEL (Lead-Ship End Cost only)

V!!1. Additional charcteristics:

Ship Service Life: $L_S := 30$ **Initial Operational Capability:** $Y_{IOC} := 1998$

Total Ship Acquisition: $N_S := 25$ **Production Rate (per year):** $R_P := 3$

Inflation:

Base Year: $Y_B := 1998$ $\quad iy := 1 .. Y_B - 1981$

Average Inflation Rate (%): $R_I := 5.$
(from 1981)

$$F_I := \prod_{iy} \left(1 + \frac{R_I}{100}\right) \qquad F_I = 2.292$$

a. Lead Ship Cost - Shipbuilder Portion:

SWBS costs: (See Table 5 for K_N factors)

Structure $\quad K_{N1} := \dfrac{.55 \cdot \mathrm{Mdol}}{\mathrm{lton}^{.772}} \quad C_{L_1} := .03395 \cdot F_I \cdot K_{N1} \cdot (W_1)^{.772} \quad C_{L_1} = 14.886 \cdot \mathrm{Mdol}$

+ Propulsion $\quad K_{N2} := \dfrac{1.2 \cdot \mathrm{Mdol}}{\mathrm{hp}^{.808}} \quad C_{L_2} := .00186 \cdot F_I \cdot K_{N2} \cdot P_{IBRAKE}^{\;.808} \quad C_{L_2} = 58.708 \cdot \mathrm{Mdol}$

+ Electric $\quad K_{N3} := \dfrac{1.0 \cdot \mathrm{Mdol}}{\mathrm{lton}^{.91}} \quad C_{L_3} := .07505 \cdot F_I \cdot K_{N3} \cdot (W_3)^{.91} \quad C_{L_3} = 34.542 \cdot \mathrm{Mdol}$

+ Command, Control, Surveillance

$K_{N4} := \dfrac{2.0 \cdot \mathrm{Mdol}}{\mathrm{lton}^{.617}} \quad C_{L_4} := .10857 \cdot F_I \cdot K_{N4} \cdot (W_4)^{.617} \quad C_{L_4} = 17.278 \cdot \mathrm{Mdol}$

(less payload GFM cost)

+ Auxiliary $\quad K_{N5} := \dfrac{1.5 \cdot \mathrm{Mdol}}{\mathrm{lton}^{.782}} \quad C_{L_5} := .09487 \cdot F_I \cdot K_{N5} \cdot (W_5)^{.782} \quad C_{L_5} = 11.189 \cdot \mathrm{Mdol}$

+ Outfit $\quad K_{N6} := \dfrac{1.0 \cdot \mathrm{Mdol}}{\mathrm{lton}^{.784}} \quad C_{L_6} := .09859 \cdot F_I \cdot K_{N6} \cdot (W_6)^{.784} \quad C_{L_6} = 9.65 \cdot \mathrm{Mdol}$

+ Armament $\quad K_{N7} := \dfrac{1.0 \cdot \mathrm{Mdol}}{\mathrm{lton}^{.987}} \quad C_{L_7} := .00838 \cdot F_I \cdot K_{N7} \cdot (W_7)^{.987} \quad C_{L_7} = 2.119 \cdot \mathrm{Mdol}$

(Less payload GFM cost)

+ Margin Cost:

$$C_{LM} := \frac{W_{M24}}{\left(W_{LS} - W_{M24}\right)} \cdot \left(\sum_{i1} C_{L_{i1}}\right) \qquad C_{LM} = 14.837 \cdot Mdol$$

+ Integration/Engineering: (Lead ship includes detail design engineering for class)

$$K_{N8} := \frac{10.0 \cdot Mdol}{Mdol^{1.099}} \qquad C_{L_8} := .034 \cdot K_{N8} \cdot \left(\sum_{i1} C_{L_{i1}} + C_{LM}\right)^{1.099} \qquad C_{L_8} = 91.894 \cdot Mdol$$

+ Ship Assembly and Support: (Lead ship includes all tooling, jigs, special facilities for class)

$$K_{N9} := \frac{2.0 \cdot Mdol}{(Mdol)^{.839}} \qquad C_{L_9} := .135 \cdot K_{N9} \cdot \left(\sum_{i1} C_{L_{i1}} + C_{LM}\right)^{.839} \qquad C_{L_9} = 19.402 \cdot Mdol$$

= <u>**Total Lead Ship Construction Cost: (BCC)**</u> **:**

$$C_{LCC} := \sum_{i1} C_{L_{i1}} + C_{L_8} + C_{L_9} + C_{LM} \qquad C_{LCC} = 274.505 \cdot Mdol$$

+ Profit:

$$F_{PROFIT} := .10 \qquad C_{LP} := F_{PROFIT} \cdot C_{LCC} \qquad C_{LP} = 27.451 \cdot Mdol$$

= <u>**Lead Ship Price**</u> **:**

$$P_L := C_{LCC} + C_{LP} \qquad P_L = 301.956 \cdot Mdol$$

+ Change Orders:

$$C_{LCORD} := .12 \cdot P_L \qquad C_{LCORD} = 36.235 \cdot Mdol$$

= <u>**Total Shipbuilder Portion:**</u>

$$C_{SB} := P_L + C_{LCORD} \qquad C_{SB} = 338.19 \cdot Mdol$$

b. Lead Ship Cost - Government Portion

Other support:

$$C_{LOTH} := .025 \cdot P_L \qquad C_{LOTH} = 7.549 \cdot Mdol$$

+ Program Manager's Growth:

$$C_{LPMG} := .1 \cdot P_L \qquad C_{LPMG} = 30.196 \cdot Mdol$$

Costed Military Payload:

$$W_{MP} := W_4 + W_7 + W_{F20} - W_{IC} - W_{F23} \qquad W_{MP} = 559.325 \cdot lton$$

+ Ordnance and Electrical GFE:
(Military Payload GFE)

$$C_{LMPG} := \left(.319 \cdot \frac{Mdol}{lton} \cdot W_{MP} + N_{HELO} \cdot 18.71 \cdot Mdol\right) \cdot F_I$$

$$C_{LMPG} = 494.72 \cdot Mdol$$

+ HM&E GFE (boats, IC): $C_{LHMEG} := .02 \cdot P_L$ $C_{LHMEG} = 6.039 \cdot Mdol$

+ Outfittimg Cost : $C_{LOUT} := .04 \cdot P_L$ $C_{LOUT} = 12.078 \cdot Mdol$

= **<u>Total Government Cost:</u>**

$C_{LGOV} := C_{LOTH} + C_{LPMG} + C_{LMPG} + C_{LHMEG} + C_{LOUT}$ $C_{LGOV} = 550.581 \cdot Mdol$

c. Total End Cost: (Must always be less than SCN appropriation)

* **<u>Total End Cost:</u>**

$C_{LEND} := C_{SB} + C_{LGOV}$ $C_{LEND} = 888.772 \cdot Mdol$

SUMMARY: INITIAL VALUES

ITERATION WEIGHT: $W_{FL} \equiv in1 \cdot lton$ $\quad ERR_{WEIGHT} = 0.102993 \quad V_{FL} \equiv W_{FL} \cdot 35 \cdot \frac{ft^3}{lton}$

$W_{FL1} = 6683 \cdot lton \quad W_T = 6058.967 \cdot lton$

GROSS CHARACTERISTICS:

$C_P \equiv .59$ **(.54 - .64)** $\quad C_{\Delta L} \equiv 55 \cdot \frac{lton}{ft^3}$ **(45 - 65)** $\quad LWL \equiv 100 \cdot \left(\frac{W_{FL}}{C_{\Delta L}}\right)^{\frac{1}{3}} \quad LWL = 495.301 \cdot ft$

$C_X \equiv .85$ **(.7 - .85)** $\quad C_V := \frac{V_{FL}}{LWL^3} \quad C_V = 1.925 \cdot 10^{-3}$

$C_{BT} \equiv 3.3$ **(2.8 - 3.7)** $\quad B \equiv \sqrt{\frac{C_{BT} \cdot V_{FL}}{C_P \cdot C_X \cdot LWL}} \quad B = 55.745 \cdot ft \quad T = 16.892 \cdot ft \quad C_{LB} = 8.885$ **(7.5 - 10)**

ENERGY BALANCE:

$V_S \equiv 27 \cdot knt \quad P_I = 102626 \cdot hp \quad P_{IREQ} = 76805.452 \cdot hp \quad ERR_{POWER} = 0.336$

$V_e \equiv 20 \cdot knt \quad kW_G = 3000 \cdot kW \quad kW_{GREQ} = 2532.648 \cdot kW \quad ERR_{KW} = 0.185$

$E \equiv 7500 \cdot knt \cdot hr$

AREA/VOLUME BALANCE:

$V_D \equiv 97715 \cdot ft^3 \quad V_T = 730369.111 \cdot ft^3 \quad V_{MB} = 70067.665 \cdot ft^3 \quad V_{TR} = 511247.364 \cdot ft^3$

$V_{DMIN} = 60754.545 \cdot ft^3 \quad V_{HT} = 632654.111 \cdot ft^3 \quad V_{AUX} = 84081.198 \cdot ft^3 \quad V_{TA} = 484091.654 \cdot ft^3$

$V_{DMAX} = 303772.727 \cdot ft^3 \quad V_{TK} = 92128.595 \cdot ft^3 \quad ERR_{AREA} = -0.053117$

$D_{10} = 34.02 \cdot ft$ **(Must be > D_{10MIN})**

$D_{10MIN} = 33.02 \cdot ft \quad A_{TR} = 56805.263 \cdot ft^2 \quad A_{HR} = 43214.262 \cdot ft^2 \quad A_{DR} = 13591.001 \cdot ft^2$

$A_{TA} = 53787.962 \cdot ft^2 \quad A_{HA} = 42930.739 \cdot ft^2 \quad A_{DA} = 10857.222 \cdot ft^2$

WEIGHT BALANCE:

$W_{FL} = 6683 \cdot lton \quad W_T = 6058.967 \cdot lton \quad ERR_{WEIGHT} = 0.102993$

$W_1 = 1958.474 \cdot lton \quad W_5 = 91.907 \cdot lton \quad W_{LS} = 3847.017 \cdot lton$

$W_2 = 556.222 \cdot lton \quad W_6 = 120.14 \cdot lton \quad W_P = 668.3 \cdot lton$

$W_3 = 339.26 \cdot lton \quad W_7 = 117.37 \cdot lton \quad W_{F41} = 1880.311 \cdot lton$

$W_4 = 313.915 \cdot lton$

STABILITY/PAYLOAD: $C_{GMB} = 0.112$ **(.09 - .122)** $\quad F_P := \frac{W_P}{W_{FL}} \quad F_P = 0.1$

MATLAB OPTIMIZER OUTPUT FOR OPTIMIZED DESIGN EXAMPLE:

```
x0 =

   55.7451   16.8924  495.3014    0.6000    0.7500


vlb =

   20.0000    5.0000  200.0000    0.5400    0.7000


vub =

   90.0000   30.0000  800.0000    0.6400    0.8500

f-COUNT   FUNCTION         MAX{g}          STEP  Procedures
    6       7627.82      0.534195           1
   12        6312.8     0.0459915           1
   18       6099.97    0.00388632           1
   24       6123.31  1.92403e-005           1
   30       6123.42  6.04933e-010           1   Hessian modified
   31       6123.42  8.88178e-016           1   Hessian modified
Optimization Converged Successfully
Active Constraints:
     2
     4
     6
     8


x =

   45.5016   12.2977  455.0163    0.5400    0.7880


options =

  1.0e+003 *

  Columns 1 through 7

    0.0010    0.0000    0.0000    0.0000         0         0         0

  Columns 8 through 14

    6.1234         0    0.0310    0.0060    0.0060         0    0.5000

  Columns 15 through 18

         0    0.0000    0.0001    0.0010
```

MIT MATH MODEL: FINAL SYNTHESIS DESIGN

$hp \equiv \frac{33000 \cdot ft \cdot lbf}{min}$ $knt \equiv 1.69 \cdot \frac{ft}{sec}$ $lton \equiv 2240 \cdot lb$

I. INPUT:

Primary Input Variables Are Highlighted in Yellow and Must Be Checked for Consistency Between MATHCAD Elements.

I1. Requirements:

Payload: (From CS2MP.XLS , Fig 1&2) $W_P := in0_1 \cdot lton$ **variable:** $W_{VP} := in0_2 \cdot lton$

Payload VCG: $VCG_P := in0_3 \cdot ft$ **Variable Payload VCG:** $VCG_{VP} := in0_4 \cdot ft$

Command and Surveillance Payload: (W_{400} less 420 and 430) $W_{P400} := in0_5 \cdot lton$ $\frac{W_{P400}}{lton} = 148.14$

Armament (all W_{700}): $W_7 := in0_6 \cdot lton$ **Armor:** $W_{164} := in0_7 \cdot lton$

Mission handling/support: $W_{P500} := in0_8 \cdot lton$ **Mission outfit:** $W_{P600} := in0_9 \cdot lton$

Ordnance: $W_{F20} := in0_{10} \cdot lton$ **(incl helo wt, WF23)** **Helo Fuel:** $W_{F42} := in0_{11} \cdot lton$

Helo's: $N_{HELO} := 2$ $W_{F23} := 12.73 \cdot lton$

Payload Cruise Electric Power Requirement: $kW_{PAY} := in0_{12} \cdot kW$

Payload Deck Areas:

Deckhouse: **C&D:** $A_{DPC} := in0_{13} \cdot ft^2$ **(W400)**

Armament: $A_{DPA} := in0_{14} \cdot ft^2$ **(W500, W600, W700, WF20)**

Hull: **C&D:** $A_{HPC} := in0_{15} \cdot ft^2$ **(W400)**

Armament: $A_{HPA} := in0_{16} \cdot ft^2$ **(W500, W600, W700, WF20)**

Manning:

Officers: $N_O := 15$ **Enlisted:** $N_E := 135$ **Total:** $N_T := N_E + N_O$ $N_T = 150$

Average deck height: $H_{DK} := 9 \cdot ft$

Sustained Speed: $V_S = 27 \cdot knt$ **(Use Figure 3 as a guide in selecting V_S)**

Endurance Speed: $V_e = 20 \cdot knt$ **Range:** $E = 7500 \cdot knt \cdot hr$

Stores period: $T_S := 45 \cdot day$

Sonar Dome/Appendages: SQS-53C; 215ft^2, 87.9lton,-1.2ft,85.7lton SQS-56; 27ft ^{2},13.94lton,-3.1ft,7.43lton

$A_{SD} := in2_5 \cdot ft^2$ water: $W_{498} := 87.9 \cdot lton$ $VCG_{498} := -1.2 \cdot ft$ structure: $W_{165} := 85.7 \cdot lton$

Fin Stabilizers: **(for one pair, electric power requirement = 50 kW)** $kW_{fins} := in2_7 \cdot kW$

Hull Material: (OS: C_{HMAT}=1.0; HTS: C_{HMAT}=0.93) $C_{HMAT} := .93$

CPS: (W_{CPS}=30lton): $W_{CPS} := 30 \cdot lton$ **(ie. No CPS=0)**

Machinery:

Number of propellers = $N_P := in2_{12}$ $C_{PROPD} := if(N_P > 1, 1.0, 1.2)$ $C_{PROPD} = 1$

Aux Propulsion (APU): $W_{237} := 0 \cdot lton$ $VCG_{237} := 0 \cdot ft$ **(Weight=14.2lton,VCG=3.5ft)**

Propulsion Engines (PE) - standard LM2500's; Generator engines DDA149TI $N_P = 2$

Number and brake horsepower of propulsion engines: $N_{PENG} := in2_{10}$ $P_{BPENG} := in2_{11} \cdot hp$

Inlet/exhaust Xsect area for PE: $A_{IE} := 135.2 \cdot ft^2$ $A_{PIE} := N_{PENG} \cdot A_{IE}$ $A_{PIE} = 540.8 \cdot ft^2$

Deckhouse decks impacted by propulsion and generator inlet/exhaust: $N_{DIE} := 1$

Hull decks impacted by propulsion inlet/exhaust: $N_{HPIE} := 0$

Machinery Box: $H_{MBMIN} := 22 \cdot ft$ $L_{MB} := 40 \cdot ft$ $N_{PENG} = 4$

$C_P = 0.54$ $C_{MB} := \dfrac{L_{MB}}{LWL}$ $C_{MB} = 0.088$ **C_{PMB} from Fig. 10:** $C_{PMB} := .998$

Ship Service Generators: $N_G := 3$ $kW_G := 3000 \cdot kW$

Hull decks impacted by generator inlet/exhaust: $N_{HeIE} := 1$

Specific fuel rate for generator engines: $FR_G := \dfrac{288}{2.54} \cdot \dfrac{lb}{kW \cdot hr}$ $FR_G = 0.085 \cdot \dfrac{lb}{hp \cdot hr}$

Inlet/exhaust X-sect area for gen: $A_{GIE} := 38.4 \cdot ft^2$ $A_{eIE} := N_G \cdot A_{GIE}$ $A_{eIE} = 115.2 \cdot ft^2$

II. GROSS CHARACTERISTICS

Hull Principle Characteristics: **(see Figures 5 and 6)**

Adjust in Summary Section at end of file

$LWL = 455.016 \cdot ft$ $B = 45.502 \cdot ft$ $C_P = 0.54$ $C_X = 0.788$

deckhouse volume: $V_D = 235516.369 \cdot ft^3$ $C_{DHMAT} := 2$

(Deckhouse Material: Aluminum - C_{DHMAT}=1; Steel - C_{DHMAT}=2)

III1.2 Seawater properties:

$T_{SW} := 59$ $\quad \rho_{SW} := 1.9905 \cdot \frac{slug}{ft^3}$ $\quad \nu_{SW} := 1.2817 \cdot 10^{-5} \cdot \frac{ft^2}{sec}$

III1.3 Resistance calculation parameters:

Correlation Allowance: $C_A := .0005$

$C_P = 0.54$

Use Figure 7 with C_P and C_{BT} for TSS wetted surface coeficient: $C_{STSS} := 2.536$

$C_{BT} = 3.7$

$S_{TSS} := C_{STSS} \cdot \sqrt{(V_{FL}) \cdot LWL}$ $\quad S_{TSS} = 17805.64 \cdot ft^2$

$V_{FL} = 108340.212 \cdot ft^3$

Specify or estimate actual ship surface area: $S_S := S_{TSS}$

Use Figure 8 or 9 with LWL for Appendage Drag Coeficient: $LWL = 455.016 \cdot ft$

$C_{DAPP} := 2.85 \cdot \frac{hp \cdot 10^{-5}}{ft^2 \cdot knt^3}$

Air Drag Coeficient: $C_{AA} := .7$

Power Margin Factor (margin for concept design = 10%): $PMF := 1.1$

III1.4 Use range of ship speeds for speed to length ratios (R_i). Reynold's numbers (RN_i) and ITTC friction (RF_i):

$i := 1..7$ $\quad V_i := i \cdot 5 \cdot knt$ $\quad$ **Ensure range includes V_e and V_S:** $\quad V_6 := V_S$ $\quad V_6 = 27 \cdot knt$

$V_4 := V_e$ $\quad V_4 = 20 \cdot knt$

$$R_i := \frac{V_i}{\sqrt{LWL}} \qquad R_{N_i} := LWL \cdot \frac{V_i}{\nu_{SW}} \qquad C_{F_i} := \frac{.075}{\left(\log\left(R_{N_i}\right) - 2\right)^2}$$

$$R_{F_i} := .5 \cdot \left[\rho_{SW} \cdot S_S \cdot \left(V_i\right)^2 \cdot \left(C_A + C_{F_i}\right)\right]$$

$\frac{V_i}{knt}$	$R_i \cdot \frac{ft^{.5}}{knt}$	R_{N_i}	C_{F_i}	$\frac{R_{F_i}}{lbf}$
5	0.234	$3 \cdot 10^8$	0.002	2894.721
10	0.469	$6 \cdot 10^8$	0.002	10793.033
15	0.703	$9 \cdot 10^8$	0.002	23354.773
20	0.938	$1.2 \cdot 10^9$	0.001	40421.138
25	1.172	$1.5 \cdot 10^9$	0.001	61888.007
27	1.266	$1.62 \cdot 10^9$	0.001	71689.062
35	1.641	$2.1 \cdot 10^9$	0.001	117732.25

III1.5 Use Gertler with C_P, C_V, R_i and C_{BT} to interpolate for C_R and calcualte TSS resistance:

$C_P = 0.54 \qquad C_V = 0.00115$

$R_i \cdot \frac{ft^{.5}}{knt}$

0.234
0.469
0.703
0.938
1.172
1.266
1.641

C_{BT}=2.25

$$C_{R2.25} := \begin{bmatrix} .00028 \\ .00028 \\ .00028 \\ .00080 \\ .00150 \\ .00335 \\ .00410 \end{bmatrix}$$

C_{BT}=3.00

$$C_{R3.00} := \begin{bmatrix} .00035 \\ .00035 \\ .00042 \\ .00100 \\ .00180 \\ .00350 \\ .00430 \end{bmatrix}$$

C_{BT}=3.75

$$C_{R3.75} := \begin{bmatrix} .00048 \\ .00048 \\ .00048 \\ .00095 \\ .00180 \\ .00360 \\ .00460 \end{bmatrix}$$

Form Factor: $FF := \frac{4}{3} \cdot \left(C_{BT} - 3\right) \qquad FF = 0.933$

$$C_{RTSS_i} := C_{R3.00_i} + FF \cdot \left(\frac{C_{R3.75_i} - C_{R2.25_i}}{2}\right) + FF^2 \cdot \left(\frac{C_{R2.25_i} + C_{R3.75_i}}{2} - C_{R3.00_i}\right)$$

$$C_{RTSS} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0.001 \\ 0.002 \\ 0.004 \\ 0.005 \end{bmatrix}$$

$$R_{RTSS_i} := .5 \cdot \left[\rho_{SW} \cdot S_S \cdot \left(V_i\right)^2 \cdot C_{RTSS_i}\right]$$

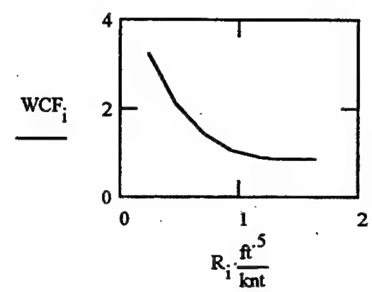
$$R_{RTSS} = \begin{bmatrix} 594.029 \\ 2376.118 \\ 5449.009 \\ 19457.936 \\ 57235.012 \\ 132640.508 \\ 283772.062 \end{bmatrix} \cdot lbf$$

III2 Calculate Bare Hull Ship Resistance - Worm Curve data from ASSET:

$$WCFA := \begin{bmatrix} .2 & 3.5 \\ .3 & 2.95 \\ .4 & 2.5 \\ .5 & 2.1 \\ .6 & 1.8 \\ .7 & 1.55 \\ .8 & 1.33 \\ .9 & 1.17 \\ 1.0 & 1.07 \\ 1.1 & 1 \\ 1.2 & .94 \\ 1.3 & .89 \\ 1.4 & .88 \\ 1.5 & .87 \\ 1.6 & .87 \end{bmatrix}$$

$iw := 1..15$

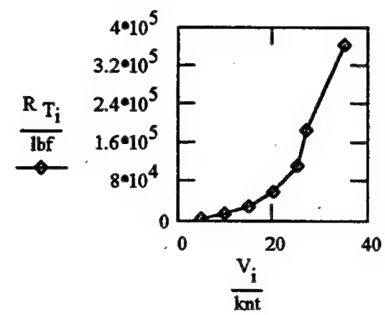
$$R = \begin{bmatrix} 0.234 \\ 0.469 \\ 0.703 \\ 0.938 \\ 1.172 \\ 1.266 \\ 1.641 \end{bmatrix} \cdot \frac{knt}{ft^{.5}} \qquad WCF := \begin{bmatrix} 3.242 \\ 2.124 \\ 1.460 \\ 1.083 \\ .923 \\ .880 \\ .870 \end{bmatrix}$$



$R_{R_i} := R_{RTSS_i} \cdot WCF_i$

$R_{T_i} := R_{F_i} + R_{R_i}$

$$R_R = \begin{bmatrix} 1925.843 \\ 5046.874 \\ 7955.554 \\ 21072.945 \\ 52827.916 \\ 116723.647 \\ 246881.694 \end{bmatrix} \cdot lbf \qquad R_T = \begin{bmatrix} 4820.565 \\ 15839.907 \\ 31310.327 \\ 61494.083 \\ 114715.923 \\ 188412.709 \\ 364613.944 \end{bmatrix} \cdot lbf$$



III3. Total Ship Effective Horsepower:

hull: $P_{EBH_i} := R_{T_i} \cdot V_i$

$$\frac{P_{EBH}}{hp} = \begin{bmatrix} 74.061 \\ 486.717 \\ 1443.121 \\ 3779.091 \\ 8812.269 \\ 15631.404 \\ 39212.572 \end{bmatrix}$$

$\frac{P_{EBH_1}}{hp} = 74.061 \qquad C_{SD} := .28$

appendage: $P_{EAPP_i} := \left(LWL \cdot D_P \cdot C_{DAPP} + .5 \cdot C_{SD} \cdot \rho_{SW} \cdot A_{SD}\right) \cdot \left(V_i\right)^3$

$$\frac{P_{EAPP}}{hp} = \begin{bmatrix} 87.773 \\ 702.188 \\ 2369.884 \\ 5617.503 \\ 10971.685 \\ 13821.164 \\ 30106.304 \end{bmatrix}$$

air: $P_{EAA_i} := .5 \cdot C_{AA} \cdot A_W \cdot \rho_A \cdot \left(V_i\right)^3$

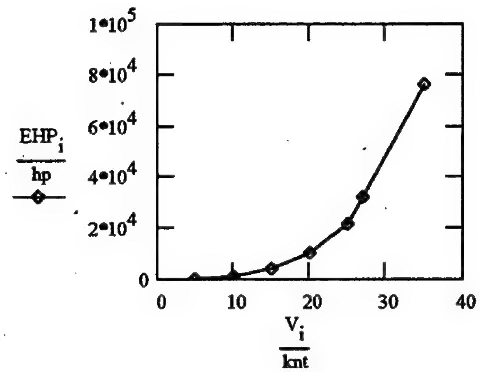
$$\frac{P_{EAA}}{hp} = \begin{bmatrix} 1.535 \\ 12.281 \\ 41.448 \\ 98.246 \\ 191.887 \\ 241.723 \\ 526.539 \end{bmatrix}$$

$P_{ET_i} := P_{EBH_i} + P_{EAPP_i} + P_{EAA_i}$

$$\frac{P_{ET}}{hp} = \begin{bmatrix} 163.37 \\ 1201.186 \\ 3854.453 \\ 9494.84 \\ 19975.841 \\ 29694.29 \\ 69845.415 \end{bmatrix}$$

$EHP_i := PMF \cdot P_{ET_i}$

$$\frac{V_i}{knt} = \begin{array}{|c|} \hline 5 \\ \hline 10 \\ \hline 15 \\ \hline 20 \\ \hline 25 \\ \hline 27 \\ \hline 35 \\ \hline \end{array} \qquad EHP = \begin{bmatrix} 179.707 \\ 1321.304 \\ 4239.898 \\ 10444.324 \\ 21973.425 \\ 32663.719 \\ 76829.957 \end{bmatrix} \cdot hp$$



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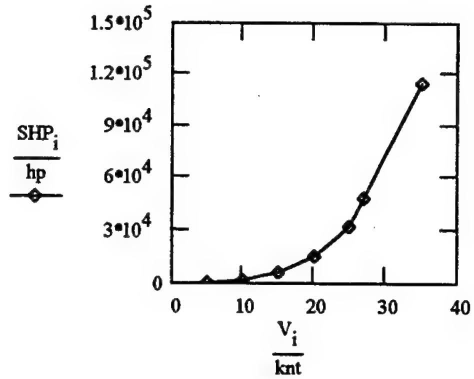
III4. Shaft Horsepower:

Approximate Propulsive Coeficient (PC): $PC := .67$ $\qquad SHP_i := \dfrac{EHP_i}{PC}$

$$SHP = \begin{bmatrix} 268.219 \\ 1972.096 \\ 6328.207 \\ 15588.543 \\ 32796.157 \\ 48751.819 \\ 114671.577 \end{bmatrix} \cdot hp$$



Endurance Shaft Horsepower: $P_e := SHP_4 \qquad P_e = 15588.543 \cdot hp$

Sustained Speed Installed Shaft Horsepower Required (Allows for fouling and sea state):

$P_S := SHP_6 \qquad P_S = 48751.819 \cdot hp \qquad P_{IREQ} := 1.25 \cdot P_S \qquad P_{IREQ} = 60939.774 \cdot hp$

Actual installed SHP must be greater than P_{IREQ}

$P_{IBRAKE} := N_{PENG} \cdot P_{BPENG} \qquad P_{IBRAKE} = 105800 \cdot hp \quad \eta := .97 \qquad P_I := \eta \cdot P_{IBRAKE} \qquad P_I = 102626 \cdot hp$

(P_I must be > P_{IREQ}) $\quad P_{IREQ} = 60939.774 \cdot hp \qquad ERR_{POWER} := \dfrac{P_I - P_{IREQ}}{P_{IREQ}} \qquad ERR_{POWER} = 0.684$

III5. Estimate Propulsion Fuel Required:
Reference: DDS 200-1 "Calculate of Surface Ship Endurance Fuel"

Average Endurance Brake SHP Required (Allows for fouling and sea state):

$$P_{eBAVG} := 1.1 \cdot \frac{P_e}{\eta} \qquad P_{eBAVG} = 17677.73 \cdot hp$$

Specific fuel rate for propulsion engines:
(GT; FR for diesel = .327)

$$FR := 1.97 \cdot \frac{lb}{hp^{.85} \cdot hr} \cdot P_{eBAVG}^{-.15} \qquad FR = 0.454 \cdot \frac{lb}{hp \cdot hr}$$

(for ICR: FR=.347 lb/hphr)

Margin for instrumentation and machinery differences, $f(P_e/P_I)$: $\quad f_1 := 1.04$

Specified fuel rate: $\quad FR_{SP} := f_1 \cdot FR$

Average fuel rate allowing for plant deterioration:

$$FR_{AVG} := 1.05 \cdot FR_{SP} \qquad FR_{AVG} = 0.496 \cdot \frac{lb}{hp \cdot hr}$$

Burnable propulsion endurance fuel weight:

$$W_{BP} := \frac{E}{V_e} \cdot \left(P_{eBAVG} \cdot FR_{AVG}\right) \qquad W_{BP} = 1468.198 \cdot lton$$

Tailpipe allowance and propulsion endurance fuel: $TPA := .95$ **(shallow tanks)**

$$W_{FP} := \frac{W_{BP}}{TPA} \qquad W_{FP} = 1545.472 \cdot lton$$

Allow for expansion and tank structure in required propulsion tank volume:

$$\gamma_F := 43 \cdot \frac{ft^3}{lton} \qquad V_{FP} := 1.02 \cdot 1.05 \cdot \gamma_F \cdot W_{FP} \qquad V_{FP} = 71173.602 \cdot ft^3$$

III6. Estimate electric load.

Reference: DDS 310-1

Estimate Maximum Functional Load based on parametrics for WINTER cruise condition:

Propulsion: $kW_P := .00466 \cdot \frac{kW}{hp} \cdot P_{IBRAKE}$ $\qquad kW_P = 493.028 \cdot kW$

Steering: $kW_S := .00583 \cdot \frac{kW}{ft^2} \cdot LWL \cdot T$ $\qquad kW_S = 32.623 \cdot kW$

Lighting: $kW_L := .0002053 \cdot \frac{kW}{ft^3} \cdot 1.8 \cdot LWL \cdot T \cdot B$ $\qquad kW_L = 94.089 \cdot kW$

Miscellaneous: $kW_M := 46.1 \cdot kW$

Heating: $kW_H := .0013 \cdot \frac{kW}{ft^3} \cdot 1.25 \cdot LWL \cdot T \cdot B$ $\qquad kW_H = 413.745 \cdot kW$

Ventilation: $kW_{CPS} := .00026 \cdot \frac{kW}{ft^3} \cdot 1.8 \cdot LWL \cdot T \cdot B$ **(zero if no CPS)** $\qquad kW_{CPS} = 119.159 \cdot kW$

$kW_V := .19 \cdot (kW_H + kW_P) + kW_{CPS}$ $\qquad kW_V = 291.445 \cdot kW$

Air Conditioning: $kW_{AC} := .67 \cdot \left(.1 \cdot kW \cdot N_T + .0015 \cdot \frac{kW}{ft^3} \cdot .47 \cdot 1.3 \cdot LWL \cdot T \cdot B + .1 \cdot kW_P\right)$

$kW_{AC} = 199.429 \cdot kW$

Aux Boiler and FW:
(electric boiler) $kW_B := .94 \cdot N_T \cdot kW$ $\qquad kW_B = 141 \cdot kW$

Firemain: $kW_F := .0001 \cdot \frac{kW}{ft^3} \cdot 1.8 \cdot LWL \cdot T \cdot B$ $\qquad kW_F = 45.83 \cdot kW$

Unrep and handling: $kW_{RH} := .00002 \cdot \frac{kW}{ft^3} \cdot 1.25 \cdot LWL \cdot T \cdot B$ $\qquad kW_{RH} = 6.365 \cdot kW$

Aux Machinery: $kW_A := .22 \cdot N_T \cdot kW + kW_{fins}$ $kW_A = 33 \cdot kW$

Services and Work Spaces: $kW_{SERV} := .35 \cdot N_T \cdot kW$ $kW_{SERV} = 52.5 \cdot kW$

Non-Payload Functional Load:

$$kW_{NP} := kW_P + kW_S + kW_L + kW_M + kW_H + kW_{CPS} + kW_V + kW_{AC} + kW_B + kW_F + kW_{RH} + kW_A + kW_S$$

Maximum Functional Load:

$kW_{MFL} := kW_{PAY} + kW_{NP}$ $kW_{MFL} = 2508.383 \cdot kW$ $\dfrac{kW_{NP}}{kW} = 1968.313$

MFL with margins: (design,growth):

$kW_{MFLM} := 1.2 \cdot 1.2 \cdot kW_{MFL}$ $kW_{MFLM} = 3612.072 \cdot kW$

Installed Electrical Power Required:

Power available per generator: $kW_G = 3000 \cdot kW$

Power required per generator: $kW_{GREQ} := \dfrac{kW_{MFLM}}{(N_G - 1) \cdot .9}$ $kW_{GREQ} = 2006.707 \cdot kW$

$ERR_{KW} := \dfrac{kW_G - kW_{GREQ}}{kW_{GREQ}}$

24 hour electrical load:

$kW_{24} := .5 \cdot (kW_{MFL} - kW_P - kW_S) + .8 \cdot (kW_P + kW_S)$ $kW_{24} = 1411.887 \cdot kW$

$ERR_{KW} = 0.495$

with margin (design): $kW_{24AVG} := 1.2 \cdot kW_{24}$ $kW_{24AVG} = 1694.264 \cdot kW$

III7. Estimate Electric Fuel Rate: $FR_G = 0.113 \cdot \dfrac{lb}{kW \cdot hr}$

Margin for instrumentation and machinery differences, f(P$_e$/P$_I$): $f_{1e} := 1.04$

Specified fuel rate: $FR_{GSP} := f_{1e} \cdot FR_G$

Average fuel rate allowing for plant deterioration:

$FR_{GAVG} := 1.05 \cdot FR_{GSP}$ $FR_{GAVG} = 0.124 \cdot \dfrac{lb}{kW \cdot hr}$ $FR_{GAVG} = 0.092 \cdot \dfrac{lb}{hp \cdot hr}$

III8. Estimate Electrical and Total fuel Required

Burnable electrical endurance fuel weight:

$W_{Be} := \dfrac{E}{V_e} \cdot (kW_{24AVG} \cdot FR_{GAVG})$ $W_{Be} = 35.119 \cdot lton$

$TPA := .95$
(shallow tanks)

Tailpipe allowance and electrical endurance fuel:

$W_{Fe} := \dfrac{W_{Be}}{TPA}$ $W_{Fe} = 36.968 \cdot lton$

Allow for expansion and tank structure in required electrical fuel tank volume:

$$V_{Fe} := 1.02\cdot 1.05\cdot \gamma_F \cdot W_{Fe} \qquad V_{Fe} = 1702.473\,\mathrm{ft}^3$$

Total ship fuel: (DFM)

$$W_{F41} := W_{FP} + W_{Fe} \qquad W_{F41} = 1582.439\,\mathrm{lton}$$

$$V_F := V_{FP} + V_{Fe} \qquad V_F = 72876.075\,\mathrm{ft}^3$$

IV. Space Estimate

IVA. Available Space

IVA1. Underwater Hull Volume Available

$$V_{HUW} := V_{FL} \qquad V_{HUW} = 108340.212\,\mathrm{ft}^3$$

IVA2. Sheer Line. (3 criteria)

1) Keep deck edge above water at 25 degree heel

2) Longitudinal strength

3) Contain machinery box height: $H_{MBMIN} = 22\,\mathrm{ft}$

$$M := \begin{bmatrix} .21\cdot B + T \\ \dfrac{LWL}{15} \\ H_{MBMIN} \end{bmatrix} \qquad M = \begin{bmatrix} 21.853 \\ 30.334 \\ 22 \end{bmatrix}\mathrm{ft} \qquad D_{10MIN} := \max(M) \qquad D_{10MIN} = 30.334\,\mathrm{ft}$$

$$D_{10} := (D_{10MIN} + 1\cdot\mathrm{ft})$$

$$D_{0MIN} := 1.011827\cdot T - 6.36215\cdot\frac{10^{-6}}{\mathrm{ft}}\cdot LWL^2 + 2.780649\cdot 10^{-2}\cdot LWL + T \qquad D_{0MIN} = 36.076\,\mathrm{ft} \qquad D_0 := D_{0MIN}$$

$$D_{20MIN} := .014\cdot LWL\cdot\left(2.125 + 1.25\cdot\frac{10^{-3}}{\mathrm{ft}}\cdot LWL\right) + T \qquad D_{20MIN} = 29.458\,\mathrm{ft} \qquad D_{20} := D_{20MIN}$$

IVA3. Above-Water Hull Volume

$$F_0 := D_0 - T \qquad F_{10} := D_{10} - T \qquad F_{20} := D_{20} - T$$

$$A_{PRO} := LWL\cdot\frac{F_0 + 4\cdot F_{10} + F_{20}}{6} \qquad F_{AV} := \frac{A_{PRO}}{LWL} \qquad F_{AV} = 19.514\,\mathrm{ft}$$

$$D_{AV} := F_{AV} + T \qquad D_{AV} = 31.812\,\mathrm{ft}$$

cubic #: $CN := \dfrac{LWL\cdot B\cdot D_{AV}}{10^5\cdot\mathrm{ft}^3}$ $\qquad CN = 6.586$

$$C_W := .236 + .836\cdot C_P \qquad C_W = 0.687$$

flare factor: $f_f := .714599 + .18098\cdot\dfrac{D_{AV}}{T} - .018828\cdot\left(\dfrac{D_{AV}}{T}\right)^2 \qquad M_f := \begin{bmatrix} f_f \\ 1 \end{bmatrix} \qquad f_f := \max(M_f) \qquad f_f = 1.057$

$$V_{HAW} := LWL\cdot B\cdot F_{AV}\cdot C_W\cdot f_f \qquad V_{HAW} = 293507.825\,\mathrm{ft}^3$$

IVA4. Total Hull Volume.

$$V_{HT} := V_{HUW} + V_{HAW} \qquad V_{HT} = 401848.037 \cdot ft^3$$

IVA5. Size Deck House:

$$V_{DMAX} := .0025 \cdot LWL^3 \qquad V_{DMAX} = 235516.298 \cdot ft^3$$

$$V_{DMIN} := .0005 \cdot LWL^3 \qquad V_{DMIN} = 47103.26 \cdot ft^3 \qquad V_D = 235516.298 \cdot ft^3$$

IVA6. Calculate Total Ship Volume

$$V_T := V_{HT} + V_D \qquad V_T = 637364.335 \cdot ft^3$$

IVB. Space Requirement

IVB1. Machinery Box **(assumed near midships)** $B_{MB} := B \quad B_{MB} = 45.502 \cdot ft$

$$H_{MB} := D_{10} \qquad L_{MB} = 40 \cdot ft \qquad A_{MB} := B \cdot T \cdot C_X + B \cdot (H_{MB} - T) \qquad A_{MB} = 1307.129 \cdot ft^2$$

Calculate Machinery Box Volume:

$$V_{MB} := L_{MB} \cdot A_{MB} \cdot C_{PMB} \qquad V_{MB} = 52180.608 \cdot ft^3 \qquad V_{AUX} := 1.2 \cdot V_{MB} \qquad V_{AUX} = 62616.73 \cdot ft^3$$

IVB2. Tankage

Helo:

Helo fuel weight from Payload Spreadsheet: $W_{F42} = 63.8 \cdot lton$

Allow for tank structure and expansion: $\gamma_{HF} := 43 \cdot \frac{ft^3}{lton}$

$$V_{HF} := 1.02 \cdot 1.05 \cdot W_{F42} \cdot \gamma_{HF} \qquad V_{HF} = 2938.181 \cdot ft^3$$

Lube Oil:

LO weight: $W_{F46} := 7.2 \cdot lton$

Allow for tank structure and expansion: $\gamma_{LO} := 39 \cdot \frac{ft^3}{lton}$

$$V_{LO} := 1.02 \cdot 1.05 \cdot W_{F46} \cdot \gamma_{LO} \qquad V_{LO} = 300.737 \cdot ft^3$$

Potable Water:

Water weight: $W_{F52} := N_T \cdot .15 \cdot lton \qquad W_{F52} = 22.5 \cdot lton$

Allow for tank structure: $\gamma_W := 36 \cdot \frac{ft^3}{lton}$

$$V_W := 1.02 \cdot W_{F52} \cdot \gamma_W \qquad V_W = 826.2 \cdot ft^3$$

Sewage: $V_{SEW} := N_T \cdot 2 \cdot ft^3 \qquad V_{SEW} = 300 \cdot ft^3$

Waste Oil: $V_{WASTE} := .005 \cdot V_{FL} \qquad V_{WASTE} = 541.701 \cdot ft^3$

Clean Balast: $V_{BAL} := .032 \cdot V_{FL} \qquad V_{BAL} := 0 \cdot ft^3 \qquad V_{BAL} = 0 \cdot ft^3$

(for compensated system)

Total:

$$V_{TK} := V_F + V_{HF} + V_{LO} + V_W + V_{SEW} + V_{WASTE} + V_{BAL} \qquad V_{TK} = 77782.894 \cdot ft^3$$

IVB3. Payload Deck Areas

Deckhouse payload area: (including access) $A_{DPR} := 1.15 \cdot A_{DPA} + 1.23 \cdot A_{DPC}$ $\quad A_{DPR} = 10143.981 \cdot ft^2$

Hull payload area: (including access) $A_{HPR} := 1.15 \cdot A_{HPA} + 1.23 \cdot A_{HPC}$ $\quad A_{HPR} = 9797.796 \cdot ft^2$

IVB4. Living Deck Area

Deckhouse: $A_{COXO} := 225 \cdot ft^2 \quad A_{DO} := 75 \cdot N_O \cdot ft^2 \quad A_{DO} = 1125 \cdot ft^2$

$A_{DL} := A_{COXO} + A_{DO} \quad A_{DL} = 1350 \cdot ft^2$

Hull: $A_{HAB} := 50 \cdot ft^2 \quad A_{HL} := \left(A_{HAB} + \frac{LWL}{100} \cdot ft\right) \cdot N_T - A_{DL}$

$A_{HL} = 6832.524 \cdot ft^2$

IVB5. Hull Stores

$$A_{HS} := 300 \cdot ft^2 + .0158 \cdot \frac{ft^2}{lb} \cdot N_T \cdot 9 \cdot \frac{lb}{day} \cdot T_S \qquad A_{HS} = 1259.85 \cdot ft^2$$

IVB6. Other Ship Functions

Deckhouse:

Maintenance:

$A_{DM} := .05 \cdot \left(A_{DPR} + A_{DL}\right) \quad A_{DM} = 574.699 \cdot ft^2$

Bridge and Chartroom:

$A_{DB} := 16 \cdot ft \cdot (B - 18 \cdot ft) \quad A_{DB} = 440.026 \cdot ft^2$

Engine Inlet/Exhaust:

$A_{DIE} := 1.4 \cdot N_{DIE} \cdot \left(A_{PIE} + A_{eIE}\right) \quad A_{DIE} = 918.4 \cdot ft^2$

Hull:

Ship Functions:

$A_{HSF} := 2500 \cdot ft^2 \cdot CN \quad A_{HSF} = 16465.835 \cdot ft^2$

Engine Inlet/Exhaust:

$A_{HIE} := 1.4 \cdot \left(N_{HPIE} \cdot A_{PIE} + N_{HeIE} \cdot A_{eIE}\right) \quad A_{HIE} = 161.28 \cdot ft^2$

IVB7. Total Required Area and Volume

Hull:

$A_{HR} := A_{HPR} + A_{HL} + A_{HS} + A_{HSF} + A_{HIE} \quad A_{HR} = 34517.285 \cdot ft^2$

$V_{HR} := H_{DK} \cdot A_{HR} \quad V_{HR} = 310655.563 \cdot ft^3$

Deckhouse:

$A_{DR} := A_{DPR} + A_{DL} + A_{DM} + A_{DB} + A_{DIE}$ $\qquad A_{DR} = 13427.106 \cdot ft^2$

$V_{DR} := H_{DK} \cdot A_{DR}$ $\qquad V_{DR} = 120843.956 \cdot ft^3$

Total:

$A_{TR} := A_{HR} + A_{DR}$ $\qquad A_{TR} = 47944.391 \cdot ft^2$

$V_{TR} := H_{DK} \cdot A_{TR}$ $\qquad V_{TR} = 431499.519 \cdot ft^3$

IVC. Space Balance

$V_D = 235516.298 \cdot ft^3$ $\qquad V_{DR} = 120843.956 \cdot ft^3$

$V_{HA} := V_{HT} - V_{MB} - V_{AUX} - V_{TK}$ $\qquad V_{HA} = 209267.805 \cdot ft^3$ $\qquad V_{HR} = 310655.563 \cdot ft^3$

$V_{TA} := V_{HA} + V_D$ $\qquad V_{TA} = 444784.103 \cdot ft^3 \quad > \quad V_{TR} = 431499.519 \cdot ft^3$

$A_{HA} := \dfrac{V_{HA}}{H_{DK}}$ $\qquad A_{HA} = 23251.978 \cdot ft^2$ $\qquad A_{HR} = 34517.285 \cdot ft^2$

$A_{DA} := \dfrac{V_D}{H_{DK}}$ $\qquad A_{DA} = 26168.478 \cdot ft^2$ $\qquad A_{DR} = 13427.106 \cdot ft^2$

$A_{TA} := A_{DA} + A_{HA}$ $\qquad A_{TA} = 49420.456 \cdot ft^2 \quad > \quad A_{TR} = 47944.391 \cdot ft^2$

$ERR_{VOL} := \dfrac{V_{TA} - V_{TR}}{V_{TR}}$ $\qquad ERR_{VOL} = 3.078702 \cdot \% \cdot$ $\qquad ERR_{AREA} := \dfrac{A_{TA} - A_{TR}}{A_{TR}} \cdot \%$

$ERR_{AREA} = 0.030787 \cdot \%$

V. Weight

V1. Propulsion (200)

Basic Machinery: (230+241/242+ 250-290) $\quad W_{BM} := P_I \cdot \dfrac{lb}{hp} \cdot \left[9.0 + 12.4 \cdot \left(P_I \cdot \dfrac{10^{-5}}{hp} - 1 \right)^2 \right]$ $\qquad W_{BM} = 412.728 \cdot lton$

Shafting: (243) $\quad f_S := .5 \qquad W_S := .356 \cdot \dfrac{lton}{ft} \cdot LWL \cdot f_S$ $\qquad W_S = 80.993 \cdot lton$

(f_S=0.5 for twin screws, 0.33 for single screw)

Props: (245)

$W_{PR} := .05575 \cdot lb \cdot \left(\dfrac{D_P}{ft} \right)^{5.497 - \frac{.0433}{ft} \cdot D_P} \cdot N_P$ $\qquad W_{PR} = 18.227 \cdot lton$

Bearings: (244) $\quad W_B := .15 \cdot (W_S + W_{PR})$ $\qquad W_B = 14.883 \cdot lton$

Total Shafting: $\quad W_{ST} := W_S + W_B + W_{PR}$ $\qquad W_{ST} = 114.103 \cdot lton$

Total Propulsion: $\quad W_2 := W_{BM} + W_{ST} + W_{237}$ $\qquad W_2 = 526.831 \cdot lton$

V2. Electrical Plant (300)

$$W_3 := 50\cdot \text{lton} + .03214\cdot\frac{\text{lton}}{\text{kW}}\cdot N_G\cdot kW_G \qquad W_3 = 339.26\ \text{lton}$$

V3. Command/Control/Surveillance (400)

Gyro/IC/Navigation (420, 430): $W_{IC} := 4.65\cdot CN\cdot\text{lton}$ $\qquad W_{IC} = 30.626\ \text{lton}$

Other/Misc Group 400: $W_{CO} := 2.24\cdot CN\cdot\text{lton}$ $\qquad W_{CO} = 14.753\ \text{lton}$

Cabling: $W_{CC} := .04\cdot\left(W_{P400} + W_{IC} + W_{CO}\right)$ $\qquad W_{CC} = 7.741\ \text{lton}$

$$W_4 := W_{P400} + W_{IC} + W_{CO} + W_{CC} + W_{498} \qquad W_4 = 289.161\ \text{lton}$$

V4. Auxiliary Systems (500)

aux steam (electric aux boiler): **hotel steam:** $Q_{HS} := 15\cdot N_T$ **distiller:** $Q_{DS} := 6.5\cdot N_T + 250$

$W_{517} := .0013\cdot\left(Q_{HS} + Q_{DS}\right)\cdot\text{lton}$ $\qquad W_{517} = 4.518\ \text{lton}$ **aux sys operating fluids:** $W_{598} := .000075\cdot V_T\cdot\frac{\text{lton}}{\text{ft}^3}$

$W_{598} = 47.802\ \text{lton}$

$$W_{AUX} := \left[.000772\cdot\left(\frac{V_T}{\text{ft}^3}\right)^{1.443} + 5.14\cdot\frac{V_T}{\text{ft}^3} + 6.19\cdot\left(\frac{V_T}{\text{ft}^3}\right)^{.7224} + 377\cdot N_T + 2.74\cdot\frac{P_I}{\text{hp}}\right]\cdot 10^{-4}\cdot\text{lton} + 113.8\cdot\text{lton}$$

$W_{AUX} = 503.173\ \text{lton}$

environmental support: $W_{593} := 10\cdot\text{lton}$ $\quad W_5 := W_{AUX} + W_{P500} + W_{517} + W_{593} + W_{598} + W_{CPS}$

$W_5 = 642.883\ \text{lton}$

V5. Outfit & Furnishings (600)

Hull Fittings: $W_{OFH} := \left(31.4 + \frac{.0003187}{\text{ft}^3}\cdot V_T\right)\cdot\text{lton}$ $\qquad W_{OFH} = 234.528\ \text{lton}$

Personnel-related: $W_{OFP} := .8\cdot\left(N_T - 9.5\right)\cdot\text{lton}$ $\qquad W_{OFP} = 112.4\ \text{lton}$

$$W_6 := W_{OFH} + W_{OFP} + W_{P600} \qquad W_6 = 354.668\ \text{lton}$$

V6. Structure (100)

Hull (110-140, 160, 190): $W_{BH} := C_{HMAT}\cdot\left(1.68341\cdot CN^2 + 167.1721\cdot CN - 103.283\right)\cdot\text{lton}$ $W_{BH} = 995.839\ \text{lton}$

$\rho_{DH} := \text{if}\left(C_{DHMAT} = 1, .0007, .001429\right)$ $\qquad \rho_{DH} = 0.001$

Deckhouse (150): $W_{DH} := \rho_{DH}\cdot\frac{\text{lton}}{\text{ft}^3}\cdot V_D$ $\qquad W_{DH} = 336.553\ \text{lton}$

Masts: $W_{171} := .0688 \cdot \frac{\text{lton}}{\text{ft}} \cdot LWL - 13.75 \cdot \text{lton}$ $\qquad W_{171} = 17.555 \,\text{lton}$

Foundations: $W_{180} := .0675 \cdot W_{BM} + .072 \cdot (W_3 + W_4 + W_5 + W_7)$ $\qquad W_{180} = 127.844 \,\text{lton}$

$$W_1 := W_{BH} + W_{DH} + W_{171} + W_{180} + W_{165} + W_{164} \qquad W_1 = 1563.49 \,\text{lton}$$

V7. Single Digit Weight Summary & Weight Balance: $\qquad i1 := 1, 2 .. 7$

Weight margin:
(Future Growth) $W_{M24} := .1 \cdot \left(\sum_{i1} W_{i1}\right)$ $\qquad W_{M24} = 383.366 \,\text{lton}$

Lightship:

$$W_{LS} := \sum_{i1} W_{i1} + W_{M24} \qquad W_{LS} = 4217.029 \,\text{lton}$$

Additional Loads:

Provisions: $W_{F31} := N_T \cdot 9 \cdot \frac{\text{lb}}{\text{day}} \cdot T_S$ $\qquad W_{F31} = 27.121 \,\text{lton}$

General stores: $W_{F32} := .0009598 \cdot \frac{\text{lton}}{\text{day}} \cdot T_S \cdot N_T$ $\qquad W_{F32} = 6.479 \,\text{lton}$

Crew: $W_{F10} := 236 \cdot \text{lb} \cdot N_E + 400 \cdot \text{lb} \cdot (N_O + 1)$ $\qquad W_{F10} = 17.08 \,\text{lton}$

$$W_T := W_{LS} + W_{F41} + W_{F42} + W_{F20} + W_{F46} + W_{F52} + W_{F31} + W_{F32} + W_{F10}$$

$$W_T = 6131.108 \,\text{lton}$$

Weight Balance: $ERR_{WEIGHT} := \frac{\Delta_{FL} - W_T}{W_T}$ $\qquad ERR_{WEIGHT} = -0.125335 \,\%$

Weights Independent of the Design Variables:

$$W_{IND} := W_{BM} + W_B + W_{237} + W_3 + W_{P400} + W_{498} + W_5 + W_6 + W_7 \ldots + W_{DH} + W_{180} + W_{165} + W_{F31} + W_{F32} + W_{F10}$$

$$W_{IND} = 2718.608 \,\text{lton}$$

VI. Stability

VI1. Calculate Light Ship Weight Group Moments:

Weight	VCG		Product
$W_{BH} = 995.839 \cdot \text{lton}$	$VCG_1 := .527 \cdot D_{10}$	$VCG_1 = 16.513 \cdot \text{ft}$	$P_1 := W_{BH} \cdot VCG_1$
$W_{DH} = 336.553 \cdot \text{lton}$	$VCG_2 := D_{10} + 1.5 \cdot H_{DK}$	$VCG_2 = 44.834 \cdot \text{ft}$	$P_2 := W_{DH} \cdot VCG_2$
$W_{180} = 127.844 \cdot \text{lton}$	$VCG_3 := .68 \cdot D_{10}$	$VCG_3 = 21.307 \cdot \text{ft}$	$P_3 := W_{180} \cdot VCG_3$
$W_{171} = 17.555 \cdot \text{lton}$	$VCG_4 := 2.65 \cdot D_{10}$	$VCG_4 = 83.036 \cdot \text{ft}$	$P_4 := W_{171} \cdot VCG_4$

$$P_{100} := P_1 + P_2 + P_3 + P_4 \qquad VCG_{100} := \frac{P_{100}}{W_1} \qquad VCG_{100} = 22.843 \cdot \text{ft}$$

$W_{BM} = 412.728 \cdot \text{lton}$	$VCG_5 := .5 \cdot D_{10}$	$VCG_5 = 15.667 \cdot \text{ft}$	$P_5 := W_{BM} \cdot VCG_5$
$W_{ST} = 114.103 \cdot \text{lton}$	$VCG_6 := 3.9 \cdot \text{ft} + .19 \cdot T$	$VCG_6 = 6.237 \cdot \text{ft}$	$P_6 := W_{ST} \cdot VCG_6$
$W_{237} = 0 \cdot \text{lton}$	$VCG_7 := VCG_{237}$	$VCG_7 = 0 \cdot \text{ft}$	$P_7 := W_{237} \cdot VCG_7$

$$P_{200} := P_5 + P_6 + P_7 \qquad VCG_{200} := \frac{P_{200}}{W_2} \qquad VCG_{200} = 13.625 \cdot \text{ft}$$

$W_3 = 339.26 \cdot \text{lton}$	$VCG_8 := .65 \cdot D_{10}$	$VCG_8 = 20.367 \cdot \text{ft}$	$P_8 := W_3 \cdot VCG_8$
$W_{IC} = 30.626 \cdot \text{lton}$	$VCG_9 := D_{10}$	$VCG_9 = 31.334 \cdot \text{ft}$	$P_9 := W_{IC} \cdot VCG_9$
$W_{CO} = 14.753 \cdot \text{lton}$	$VCG_{10} := 5.6 \cdot \text{ft} + .4625 \cdot D_{10}$	$VCG_{10} = 20.092 \cdot \text{ft}$	$P_{10} := W_{CO} \cdot VCG_{10}$
$W_{CC} = 7.741 \cdot \text{lton}$	$VCG_{11} := .5 \cdot D_{10}$	$VCG_{11} = 15.667 \cdot \text{ft}$	$P_{11} := W_{CC} \cdot VCG_{11}$
$W_{498} = 87.9 \cdot \text{lton}$	$VCG_{12} := VCG_{498}$	$VCG_{12} = -1.2 \cdot \text{ft}$	$P_{12} := W_{498} \cdot VCG_{12}$
$W_{AUX} = 503.173 \cdot \text{lton}$	$VCG_{13} := .9 \cdot (D_{10} - 7.4 \cdot \text{ft})$	$VCG_{13} = 21.541 \cdot \text{ft}$	$P_{13} := W_{AUX} \cdot VCG_{13}$
$W_{517} = 4.518 \cdot \text{lton}$	$VCG_{14} := .5 \cdot H_{MB}$	$VCG_{14} = 15.667 \cdot \text{ft}$	$P_{14} := W_{517} \cdot VCG_{14}$
$W_{OFH} = 234.528 \cdot \text{lton}$	$VCG_{15} := .805 \cdot D_{10}$	$VCG_{15} = 25.224 \cdot \text{ft}$	$P_{15} := W_{OFH} \cdot VCG_{15}$
$W_{OFP} = 112.4 \cdot \text{lton}$	$VCG_{16} := 8 \cdot \text{ft} + .71 \cdot D_{10}$	$VCG_{16} = 30.247 \cdot \text{ft}$	$P_{16} := W_{OFP} \cdot VCG_{16}$

$$ip := 1 .. 16$$

$$P_{WG} := \sum_{ip} P_{ip} + W_P \cdot VCG_P - W_{VP} \cdot VCG_{VP} \qquad P_{WG} = 80422.723 \cdot \text{lton} \cdot \text{ft}$$

VI2. Light Ship KG

$VCG_{LS} := \dfrac{P_{WG}}{\sum_{i1} W_{i1}}$ $\quad VCG_{LS} = 20.978\,ft \qquad KG_{LS} := VCG_{LS} \qquad KG_{LS} = 20.978\,ft$

VI3. Calculate Variable Load Weight Group Moments:

Weight	VCG		Product
$W_{F10} = 17.08\,lton$	$VCG_{17} := .746 \cdot D_{10}$	$VCG_{17} = 23.375\,ft$	$P_{17} := W_{F10} \cdot VCG_{17}$
$W_{F31} = 27.121\,lton$	$VCG_{18} := .55 \cdot D_{10}$	$VCG_{18} = 17.234\,ft$	$P_{18} := W_{F31} \cdot VCG_{18}$
$W_{F32} = 6.479\,lton$	$VCG_{19} := .65 \cdot D_{10}$	$VCG_{19} = 20.367\,ft$	$P_{19} := W_{F32} \cdot VCG_{19}$
$W_{F41} = 1582.439\,lton$	$VCG_{20} := 7.5 \cdot ft$	$VCG_{20} = 7.5\,ft$	$P_{20} := W_{F41} \cdot VCG_{20}$
$W_{F42} = 63.8\,lton$	$VCG_{21} := 10. \cdot ft$	$VCG_{21} = 10\,ft$	$P_{21} := W_{F42} \cdot VCG_{21}$
$W_{F46} = 7.2\,lton$	$VCG_{22} := .35 \cdot D_{10}$	$VCG_{22} = 10.967\,ft$	$P_{22} := W_{F46} \cdot VCG_{22}$
$W_{F52} = 22.5\,lton$	$VCG_{23} := 7.5 \cdot ft$	$VCG_{23} = 7.5\,ft$	$P_{23} := W_{F52} \cdot VCG_{23}$

$iL := 17..23 \qquad P_{WGL} := \sum_{iL} P_{iL} + W_{VP} \cdot VCG_{VP} \qquad P_{WGL} = 21193.169\,lton \cdot ft$

$W_L := W_{F41} + W_{F42} + W_{F20} + W_{F46} + W_{F52} + W_{F31} + W_{F32} + W_{F10} \qquad W_L = 1914.079\,lton$

$VCG_L := \dfrac{P_{WGL}}{W_L} \qquad VCG_L = 11.072\,ft$

VI4. Calculate Ship Stability Characteristics:

$KG_{MARG} := .5 \cdot ft \quad KG := \dfrac{W_{LS} \cdot KG_{LS} + W_L \cdot VCG_L}{W_T} + KG_{MARG} \quad C_{IT} := -.497 + 1.44 \cdot C_W \quad C_{IT} = 0.493$

$KB := \dfrac{T}{3} \cdot \left(2.5 - \dfrac{C_P \cdot C_X}{C_W} \right) \quad BM := \dfrac{LWL \cdot B^3 \cdot C_{IT}}{12 \cdot V_{FL}} \quad GM := KB + BM - KG \quad C_{GMB} := \dfrac{GM}{B}$

$KG = 18.386\,ft \qquad KB = 7.711\,ft \qquad BM = 16.252\,ft \qquad GM = 5.577\,ft \qquad C_{GMB} = 0.123$

$Mdol := coul$ $\qquad Kdol := \frac{Mdol}{1000}$

$Bdol := 1000 \cdot Mdol$ $\qquad dol := \frac{Kdol}{1000}$

VII. VERY SIMPLIFIED COST MODEL (Lead-Ship End Cost only)

V!!1. Additional charcteristics:

Ship Service Life: $L_S := 30$ **Initial Operational Capability:** $Y_{IOC} := 1998$

Total Ship Acquisition: $N_S := 25$ **Production Rate (per year):** $R_P := 3$

Inflation:

Base Year: $Y_B := 1998$ $\quad iy := 1 .. Y_B - 1981$

Average Inflation Rate (%): $R_I := 5.$
(from 1981)

$$F_I := \prod_{iy} \left(1 + \frac{R_I}{100}\right) \qquad F_I = 2.292$$

a. Lead Ship Cost - Shipbuilder Portion:

SWBS costs: (See Table 5 for K_N factors)

Structure $\quad K_{N1} := \frac{.55 \cdot Mdol}{lton^{.772}} \quad C_{L_1} := .03395 \cdot F_I \cdot K_{N1} \cdot (W_1)^{.772} \quad C_{L_1} = 12.51 \cdot Mdol$

+ Propulsion $\quad K_{N2} := \frac{1.2 \cdot Mdol}{hp^{.808}} \quad C_{L_2} := .00186 \cdot F_I \cdot K_{N2} \cdot P_{IBRAKE}^{.808} \quad C_{L_2} = 58.708 \cdot Mdol$

+ Electric $\quad K_{N3} := \frac{1.0 \cdot Mdol}{lton^{.91}} \quad C_{L_3} := .07505 \cdot F_I \cdot K_{N3} \cdot (W_3)^{.91} \quad C_{L_3} = 34.542 \cdot Mdol$

+ Command, Control, Surveillance

$K_{N4} := \frac{2.0 \cdot Mdol}{lton^{.617}} \quad C_{L_4} := .10857 \cdot F_I \cdot K_{N4} \cdot (W_4)^{.617} \quad C_{L_4} = 16.424 \cdot Mdol$

(less payload GFM cost)

+ Auxiliary $\quad K_{N5} := \frac{1.5 \cdot Mdol}{lton^{.782}} \quad C_{L_5} := .09487 \cdot F_I \cdot K_{N5} \cdot (W_5)^{.782} \quad C_{L_5} = 51.215 \cdot Mdol$

+ Outfit $\quad K_{N6} := \frac{1.0 \cdot Mdol}{lton^{.784}} \quad C_{L_6} := .09859 \cdot F_I \cdot K_{N6} \cdot (W_6)^{.784} \quad C_{L_6} = 22.548 \cdot Mdol$

+ Armament $K_{N7} := \frac{1.0 \cdot Mdol}{lton^{.987}}$ $C_{L_7} := .00838 \cdot F_I \cdot K_{N7} \cdot (W_7)^{.987}$ $C_{L_7} = 2.119 \cdot Mdol$

(Less payload GFM cost)

+ Margin Cost:

$$C_{LM} := \frac{W_{M24}}{(W_{LS} - W_{M24})} \cdot \left(\sum_{i1} C_{L_{i1}}\right)$$ $C_{LM} = 19.807 \cdot Mdol$

+ Integration/Engineering: (Lead ship includes detail design engineering for class)

$K_{N8} := \frac{10.0 \cdot Mdol}{Mdol^{1.099}}$ $C_{L_8} := .034 \cdot K_{N8} \cdot \left(\sum_{i1} C_{L_{i1}} + C_{LM}\right)^{1.099}$ $C_{L_8} = 126.231 \cdot Mdol$

+ Ship Assembly and Support: (Lead ship includes all tooling, jigs, special facilities for class)

$K_{N9} := \frac{2.0 \cdot Mdol}{(Mdol)^{.839}}$ $C_{L_9} := .135 \cdot K_{N9} \cdot \left(\sum_{i1} C_{L_{i1}} + C_{LM}\right)^{.839}$ $C_{L_9} = 24.724 \cdot Mdol$

= <u>Total Lead Ship Construction Cost: (BCC)</u> :

$$C_{LCC} := \sum_{i1} C_{L_{i1}} + C_{L_8} + C_{L_9} + C_{LM}$$ $C_{LCC} = 368.828 \cdot Mdol$

+ Profit:

$F_{PROFIT} := .10$ $C_{LP} := F_{PROFIT} \cdot C_{LCC}$ $C_{LP} = 36.883 \cdot Mdol$

= <u>Lead Ship Price</u> :

$P_L := C_{LCC} + C_{LP}$ $P_L = 405.711 \cdot Mdol$

+ Change Orders:

$C_{LCORD} := .12 \cdot P_L$ $C_{LCORD} = 48.685 \cdot Mdol$

= <u>Total Shipbuilder Portion:</u>

$C_{SB} := P_L + C_{LCORD}$ $C_{SB} = 454.396 \cdot Mdol$

b. Lead Ship Cost - Government Portion

Other support: $C_{LOTH} := .025 \cdot P_L$ $C_{LOTH} = 10.143 \cdot Mdol$

+ Program Manager's Growth: $C_{LPMG} := .1 \cdot P_L$ $C_{LPMG} = 40.571 \cdot Mdol$

Costed Military Payload: $W_{MP} := W_4 + W_7 + W_{F20} - W_{IC} - W_{F23}$ $\quad W_{MP} = 550.634 \cdot lton$

+ Ordnance and Electrical GFE:
(Military Payload GFE)

$$C_{LMPG} := \left(.319 \cdot \frac{Mdol}{lton} \cdot W_{MP} + N_{HELO} \cdot 18.71 \cdot Mdol\right) \cdot F_I$$

$$C_{LMPG} = 488.366 \cdot Mdol$$

+ HM&E GFE (boats, IC): $C_{LHMEG} := .02 \cdot P_L$ $\quad C_{LHMEG} = 8.114 \cdot Mdol$

+ Outfittimg Cost : $C_{LOUT} := .04 \cdot P_L$ $\quad C_{LOUT} = 16.228 \cdot Mdol$

= **Total Government Cost:**

$$C_{LGOV} := C_{LOTH} + C_{LPMG} + C_{LMPG} + C_{LHMEG} + C_{LOUT} \qquad C_{LGOV} = 563.422 \cdot Mdol$$

c. Total End Cost: (Must always be less than SCN appropriation)

* **Total End Cost:**

$$C_{LEND} := C_{SB} + C_{LGOV} \qquad C_{LEND} = 1017.818 \cdot Mdol$$

SUMMARY: FINAL SYSTHESIS DESIGN

ITERATION WEIGHT:

$W_{FL1} = 6683 \cdot lton$ $\quad W_{FL} \equiv in1_1 \cdot lton$ $\quad W_{FL} = 6123.424 \cdot lton$ $\quad W_T = 6131.108 \cdot lton$ $\quad ERR_{WEIGHT} = -0.125335 \cdot \%$

GROSS CHARACTERISTICS:

$C_P \equiv in1_5$ **(.54 - .64)** $\quad C_{\Delta L} \equiv 55 \cdot \frac{lton}{ft^3}$ **(45 - 65)** $\quad LWL \equiv in1_4 \cdot ft$ $\quad LWL = 455.016 \cdot ft$

$C_X \equiv in1_6$ **(.7 - .85)** $\quad C_V := \frac{V_{FL}}{LWL^3}$ $\quad C_V = 1.15 \cdot 10^{-3}$ $\quad V_{FL} = 108340.212 \cdot ft^3$

$C_{BT} \equiv in1_7$ **(2.8 - 3.7)** $\quad B \equiv in1_2 \cdot ft$ $\quad B = 45.502 \cdot ft$ $\quad T = 12.298 \cdot ft$ $\quad C_{LB} = 10$ **(7.5 - 10)**

$V_{FL} \equiv B \cdot T \cdot LWL \cdot C_X \cdot C_P$ $\quad V_{FL} = 108340.212 \cdot ft^3$

ENERGY BALANCE:

$V_S \equiv in2_2 \cdot knt$ $\quad P_I = 102626 \cdot hp$ $\quad P_{IREQ} = 60939.774 \cdot hp$ $\quad ERR_{POWER} = 68.406 \cdot \%$

$V_e \equiv in2_3 \cdot knt$ $\quad kW_G = 3000 \cdot kW$ $\quad kW_{GREQ} = 2006.707 \cdot kW$ $\quad ERR_{KW} = 49.499 \cdot \%$

$E \equiv in2_4 \cdot knt \cdot hr$

AREA/VOLUME BALANCE:

$V_D \equiv .0025 \cdot LWL^3$ $\quad V_T = 637364.335 \cdot ft^3$ $\quad V_{MB} = 52180.608 \cdot ft^3$ $\quad V_{TR} = 431499.519 \cdot ft^3$

$V_{DMIN} = 47103.26 \cdot ft^3$ $\quad V_{HT} = 401848.037 \cdot ft^3$ $\quad V_{AUX} = 62616.73 \cdot ft^3$ $\quad V_{TA} = 444784.103 \cdot ft^3$

$V_{DMAX} = 235516.298 \cdot ft^3$ $\quad V_{TK} = 77782.894 \cdot ft^3$ $\quad ERR_{AREA} = 0.030787 \cdot \%$

$D_{10} = 31.334 \cdot ft$ **(Must be > D_{10MIN})**

$D_{10MIN} = 30.334 \cdot ft$ $\quad A_{TR} = 47944.391 \cdot ft^2$ $\quad A_{HR} = 34517.285 \cdot ft^2$ $\quad A_{DR} = 13427.106 \cdot ft^2$

$A_{TA} = 49420.456 \cdot ft^2$ $\quad A_{HA} = 23251.978 \cdot ft^2$ $\quad A_{DA} = 26168.478 \cdot ft^2$

WEIGHT BALANCE:

$W_{FL} = 6123.424 \cdot lton$ $\quad W_T = 6131.108 \cdot lton$ $\quad ERR_{WEIGHT} = -0.125335 \cdot \%$

$W_1 = 1563.49 \cdot lton$ $\quad W_5 = 642.883 \cdot lton$ $\quad W_{LS} = 4217.029 \cdot lton$

$W_2 = 526.831 \cdot lton$ $\quad W_6 = 354.668 \cdot lton$ $\quad W_P = 668.3 \cdot lton$

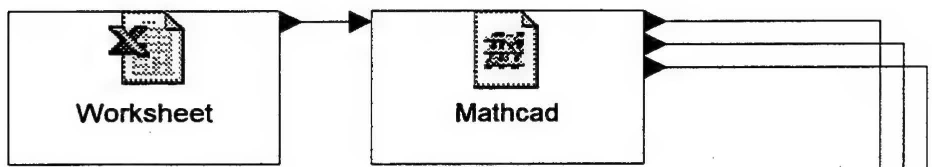
$W_3 = 339.26 \cdot lton$ $\quad W_7 = 117.37 \cdot lton$ $\quad W_{F41} = 1582.439 \cdot lton$

$W_4 = 289.161 \cdot lton$

STABILITY/PAYLOAD:

$C_{GMB} = 0.123$ **(.09 - .122)** $\quad F_P := \frac{W_P}{W_{FL}} \cdot 100$ $\quad F_P = 10.9138$

NON-OPTIMZED MATH MODEL



Payload Characteristics

MIT Math Model

8359.5	Wfl	102626	Pinstalled	12.68761	GM
62.24415	Beam	85806.68	Prequired	19.66128	KG
19.15205	Draft	3000	kWinstld	11.95712	KB
532.1307	LWL	3023.539	kWreqrd	20.39177	BM
0.59	Cp (fixed)	0.204919	Area Error	2.04E-01	Cgmb
0.775	Cx (fixed)	-0.00863	Wgt Error	8.064061	Payload %
3.25	Cbt (fixed)			1103.22	Cost, $Mil
8.549088	Clb			6	# of Iter
55	Cdisp/l (fixed)				

End of Analysis

Final Design Summary, Without Optimization

MIT MATH MODEL: NO OPTIMIZATION

$hp \equiv \frac{33000 \cdot ft \cdot lbf}{min}$ $knt \equiv 1.69 \cdot \frac{ft}{sec}$ $lton \equiv 2240 \cdot lb$

I. INPUT

 # = Primary Input Variables

= Check after every iteration

I1. Requirements:

Payload: (From CS2MP.XLS, Fig 1&2**)** $W_P := in0_1 \cdot lton$ **variable:** $W_{VP} := in0_2 \cdot lton$

Payload VCG: $VCG_P := in0_3 \cdot ft$ **Variable Payload VCG:** $VCG_{VP} := in0_4 \cdot ft$

Command and Surveillance Payload: $W_{P400} := in0_5 \cdot lton$
(W_{400} less 420 and 430)

Armament (all W_{700}): $W_7 := in0_6 \cdot lton$ **Armor:** $W_{164} := in0_7 \cdot lton$

Mission handling/support: $W_{P500} := in0_8 \cdot lton$ **Mission outfit:** $W_{P600} := in0_9 \cdot lton$

Ordnance: $W_{F20} := in0_{10} \cdot lton$ **(incl helo wt, WF23)** **Helo Fuel:** $W_{F42} := in0_{11} \cdot lton$

Helo's: $N_{HELO} := 2$ $W_{F23} := 12.73 \cdot lton$

Payload Cruise Electric Power Requirement: $kW_{PAY} := in0_{12} \cdot kW$

Payload Deck Areas:

Deckhouse: **C&D:** $A_{DPC} := in0_{13} \cdot ft^2$ **(W400)**

Armament: $A_{DPA} := in0_{14} \cdot ft^2$ **(W500, W600, W700, WF20)**

Hull: **C&D:** $A_{HPC} := in0_{15} \cdot ft^2$ **(W400)**

Armament: $A_{HPA} := in0_{16} \cdot ft^2$ **(W500, W600, W700, WF20)**

Manning:

Officers: $N_O := 15$ **Enlisted:** $N_E := 135$ **Total:** $N_T := N_E + N_O$ $N_T = 150$

Average deck height: $H_{DK} := 9 \cdot ft$

Sustained Speed: $V_S = 27 \cdot knt$ **(Use Figure 3 as a guide in selecting V_S)**

Endurance Speed: $V_e = 20 \cdot knt$ **Range:** $E = 7500 \cdot knt \cdot hr$

Stores period: $T_S := 45 \cdot day$

Sonar Dome/Appendages: **SQS-56 Sonar:** $A_{SD} := 215 \cdot ft^2$ **(SQS-56: 27ft²; SQS-53C: 215ft²)**

water: $W_{498} := 87.9 \cdot lton$ $VCG_{498} := -1.2 \cdot ft$ **structure:** $W_{165} := 85.7 \cdot lton$

Fin Stabilizers: **(for one pair, electric power requirement = 50 kW)** $kW_{fins} := 0 \cdot kW$

Hull Material: (OS: C_{HMAT}=1.0; HTS: C_{HMAT}=0.93) $C_{HMAT} := .93$

CPS: (W_{CPS}=30lton): $W_{CPS} := 30 \cdot lton$ **(ie. no CPS)**

Machinery:

Number of propellers = $N_P := 2$ $C_{PROPD} := if(N_P > 1, 1.0, 1.2)$ $C_{PROPD} = 1$

Aux Propulsion (APU): $W_{237} := 0 \cdot lton$ $VCG_{237} := 0 \cdot ft$

Propulsion Engines (PE) - standard LM2500's; Generator engines DDA149TI

Number and brake horsepower of propulsion engines: $N_{PENG} := 4$ $P_{BPENG} := 26450 \cdot hp$

Inlet/exhaust Xsect area for PE: $A_{IE} := 135.2 \cdot ft^2$ $A_{PIE} := N_{PENG} \cdot A_{IE}$ $A_{PIE} = 540.8 \, ft^2$

Deckhouse decks impacted by propulsion and generator inlet/exhaust: $N_{DIE} := 1$

Hull decks impacted by propulsion inlet/exhaust: $N_{HPIE} := 0$

Machinery Box: $H_{MBMIN} := 22 \cdot ft$ $L_{MB} := 40 \cdot ft$

$C_P = 0.59$ $C_{MB} := \dfrac{L_{MB}}{LWL}$ $C_{MB} = 0.075$ **C_{PMB} from Fig. 10:** $C_{PMB} := .998$ #

Ship Service Generators: $N_G := 3$ $kW_G := 3000 \cdot kW$

Hull decks impacted by generator inlet/exhaust: $N_{HeIE} := 1$

Specific fuel rate for generator engines: $FR_G := \dfrac{.288}{2.54} \cdot \dfrac{lb}{kW \cdot hr}$ $FR_G = 0.085 \, \dfrac{lb}{hp \cdot hr}$

Inlet/exhaust X-sect area for gen: $A_{GIE} := 38.4 \cdot ft^2$ $A_{eIE} := N_G \cdot A_{GIE}$ $A_{eIE} = 115.2 \, ft^2$

II. GROSS CHARACTERISTICS

Hull Principle Characteristics: **(see Figures 5 and 6)** **Adjust in Summary Section at end of file**

$LWL = 532.131 \, ft$ $B = 62.244 \, ft$ $C_P = 0.59$ $C_X = 0.775$

deckhouse volume: $V_D = 190000 \, ft^3$ $C_{DHMAT} := 2$

(Deckhouse Material: Aluminum - C_{DHMAT}=1; Steel - C_{DHMAT}=2)

II1. Complete Principle Characteristics:

Choose Payload Weight Fraction from Figure 4 and Calculate Full Load Weight (1st Iteration only, set W_{FL}=W_{FL1} in Summary section at end of file).

$$F_P := .1 \qquad W_{FL1} := \frac{W_P}{F_P} \qquad W_{FL1} = 6683 \cdot \text{lton}$$

Specify Full Load Weight (subsequent iterations set W_{FL}=W_T from prior iteration in Summary at end of file):

$$W_{FL} = 8287.388 \cdot \text{lton} \qquad V_{FL} := B \cdot T \cdot LWL \cdot C_P \cdot C_X$$

##

Calculate Full Load Displacement and Volume at LWL:

$$\Delta_{FL} := W_{FL} \qquad V_{FL} := \Delta_{FL} \cdot 35 \cdot \frac{\text{ft}^3}{\text{lton}} \qquad V_{FL} = 290058.58 \cdot \text{ft}^3$$

Calculate Draft (LWL):

$$T := \frac{V_{FL}}{C_P \cdot C_X \cdot LWL \cdot B} \qquad T = 19.152 \cdot \text{ft}$$

II2. Calculate Displacement to Length Ratio and Compare to Figure 5:

$$C_{\Delta L} := \frac{\Delta_{FL}}{\left(\frac{LWL}{100}\right)^3} \qquad C_{\Delta L} = 55 \cdot \frac{\text{lton}}{\text{ft}^3} \qquad \textbf{(45-65)}$$

II3. Calculate Speed to Length Ratio and C_V:

$$R_{VL} := \frac{V_S}{\sqrt{LWL}} \qquad R_{VL} = 1.17 \cdot \frac{\text{knt}}{\text{ft}^{.5}} \qquad C_V := \frac{V_{FL}}{LWL^3} \qquad C_V = 0.001925$$

II4. Calculate Beam to Draft Ratio and Compare to Tables 1-4:

$$C_{BT} := \frac{B}{T} \qquad C_{BT} = 3.25 \qquad \textbf{(2.8-3.7)}$$

II5. Calculate Length to Beam Ratio:

$$C_{LB} := \frac{LWL}{B} \qquad C_{LB} = 8.549 \qquad \textbf{(7.5-10)}$$

<u>III. ENERGY (Uses Taylor Standard Series (TSS)</u>

References: DDS 051-1 and Taylor Reanalysis by Gertler

III1. Calculate TSS Resistance:

III1.1 Estimate propeller diameter and frontal area of ship:

$$C_{PROPD} = 1 \qquad D_P := (.662 \cdot T + .012 \cdot LWL) \cdot C_{PROPD} \qquad D_P = 19.064 \cdot \text{ft}$$

Frontal area of ship = $A_W := B \cdot (3 \cdot T) \qquad A_W = 3576.308 \cdot \text{ft}^2 \qquad \rho_A := .0023817 \cdot \frac{\text{slug}}{\text{ft}^3}$

III1.2 Seawater properties:

$T_{SW} := 59$ $\qquad \rho_{SW} := 1.9905 \cdot \frac{slug}{ft^3}$ $\qquad \nu_{SW} := 1.2817 \cdot 10^{-5} \cdot \frac{ft^2}{sec}$

III1.3 Resistance calculation parameters:

Correlation Allowance: $C_A := .0005$ $\qquad C_P = 0.59$

Use Figure 7 with C_P and C_{BT} for TSS wetted surface coeficient: $\qquad C_{STSS} := 2.536$ ##

$C_{BT} = 3.25$

$S_{TSS} := C_{STSS} \cdot V_{FL}^{.5} \cdot LWL^{.5}$ $\qquad S_{TSS} = 31506.581 \cdot ft^2$

Specify or estimate actual ship surface area: $\qquad S_S := S_{TSS}$ #

Use Figure 8 or 9 with LWL for Appendage Drag Coeficient: $\qquad LWL = 532.131 \cdot ft$

$C_{DAPP} := 2.85 \cdot \frac{hp \cdot 10^{-5}}{ft^2 \cdot knt^3}$ ##

Air Drag Coeficient: $\qquad C_{AA} := .7$

Power Margin Factor (margin for concept design = 10%): $\qquad PMF := 1.05$

III1.4 Use range of ship speeds for speed to length ratios (R_i). Reynold's numbers (RN_i) and ITTC friction (RF_i):

$i := 1 .. 7$ $\qquad V_i := i \cdot 5 \cdot knt$ $\qquad$ **Ensure range includes V_e and V_S:** $\qquad V_6 := V_S \quad V_6 = 27 \cdot knt$ ##

$V_4 := V_e \quad V_4 = 20 \cdot knt$

$$R_i := \frac{V_i}{\sqrt{LWL}} \qquad R_{N_i} := LWL \cdot \frac{V_i}{\nu_{SW}} \qquad C_{F_i} := \frac{.075}{\left(\log\left(R_{N_i}\right) - 2\right)^2}$$

$$R_{F_i} := .5 \cdot \left[\rho_{SW} \cdot S_S \cdot \left(V_i\right)^2 \cdot \left(C_A + C_{F_i}\right)\right]$$

$\frac{V_i}{knt}$	$R_i \cdot \frac{ft^{.5}}{knt}$	R_{N_i}	C_{F_i}	$\frac{R_{F_i}}{lbf}$
5	0.217	$3.508 \cdot 10^8$	0.002	5039.4
10	0.434	$7.016 \cdot 10^8$	0.002	18809.018
15	0.65	$1.052 \cdot 10^9$	0.002	40723.396
20	0.867	$1.403 \cdot 10^9$	0.001	70508.886
25	1.084	$1.754 \cdot 10^9$	0.001	107985.975
27	1.17	$1.894 \cdot 10^9$	0.001	125099.7
35	1.517	$2.456 \cdot 10^9$	0.001	205513.005

III1.5 Use Gertler with C_P, C_V, R_i and C_{BT} to interpolate for C_R and calcualte TSS resistance:

$C_P = 0.59 \qquad C_V = 0.001925$

$R_i \cdot \frac{ft^{.5}}{knt}$
0.217
0.434
0.65
0.867
1.084
1.17
1.517

C_{BT}=2.25 $\qquad$ **C_{BT}=3.00** $\qquad$ **C_{BT}=3.75**

$$C_{R2.25} := \begin{bmatrix} .00028 \\ .00028 \\ .00028 \\ .00080 \\ .00150 \\ .00335 \\ .00410 \end{bmatrix} \qquad C_{R3.00} := \begin{bmatrix} .00035 \\ .00035 \\ .00042 \\ .00100 \\ .00180 \\ .00350 \\ .00430 \end{bmatrix} \qquad C_{R3.75} := \begin{bmatrix} .00048 \\ .00048 \\ .00048 \\ .00095 \\ .00180 \\ .00360 \\ .00460 \end{bmatrix}$$

##

Form Factor: $\qquad FF := \frac{4}{3} \cdot (C_{BT} - 3) \qquad FF = 0.333$

$$C_{RTSS_i} := C_{R3.00_i} + FF \cdot \left(\frac{C_{R3.75_i} - C_{R2.25_i}}{2} \right) + FF^2 \cdot \left(\frac{C_{R2.25_i} + C_{R3.75_i}}{2} - C_{R3.00_i} \right)$$

$$C_{RTSS} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0.001 \\ 0.002 \\ 0.004 \\ 0.004 \end{bmatrix} \qquad R_{RTSS_i} := .5 \cdot \left[\rho_{SW} \cdot S_S \cdot (V_i)^2 \cdot C_{RTSS_i} \right] \qquad R_{RTSS} = \begin{bmatrix} 865.732 \\ 3462.929 \\ 9045.41 \\ 36221.442 \\ 102619.128 \\ 231047.526 \\ 481501.386 \end{bmatrix} \cdot lbf$$

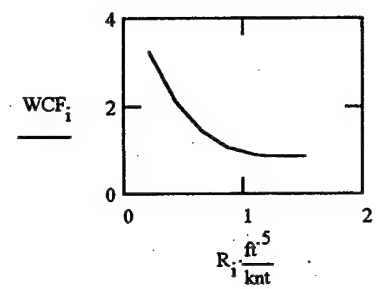
III2 Calculate Bare Hull Ship Resistance - Worm Curve data from ASSET:

$$WCFA := \begin{bmatrix} .2 & 3.5 \\ .3 & 2.95 \\ .4 & 2.5 \\ .5 & 2.1 \\ .6 & 1.8 \\ .7 & 1.55 \\ .8 & 1.33 \\ .9 & 1.17 \\ 1.0 & 1.07 \\ 1.1 & 1 \\ 1.2 & .94 \\ 1.3 & .89 \\ 1.4 & .88 \\ 1.5 & .87 \\ 1.6 & .87 \end{bmatrix}$$

$$iw := 1 .. 15$$

$$R = \begin{bmatrix} 0.217 \\ 0.434 \\ 0.65 \\ 0.867 \\ 1.084 \\ 1.17 \\ 1.517 \end{bmatrix} \cdot \frac{knt}{ft^{.5}} \qquad WCF := \begin{bmatrix} 3.242 \\ 2.124 \\ 1.460 \\ 1.083 \\ .923 \\ .880 \\ .870 \end{bmatrix}$$

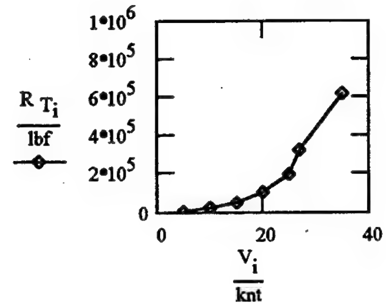
##



$$R_{R_i} := R_{RTSS_i} \cdot WCF_i$$

$$R_{T_i} := R_{F_i} + R_{R_i}$$

$$R_R = \begin{bmatrix} 2806.704 \\ 7355.261 \\ 13206.298 \\ 39227.822 \\ 94717.455 \\ 203321.823 \\ 418906.206 \end{bmatrix} \cdot lbf \qquad R_T = \begin{bmatrix} 7846.104 \\ 26164.279 \\ 53929.694 \\ 109736.708 \\ 202703.429 \\ 328421.523 \\ 624419.211 \end{bmatrix} \cdot lbf$$



III3. Total Ship Effective Horsepower:

hull: $P_{EBH_i} := R_{T_i} \cdot V_i$ $\qquad \frac{P_{EBH}}{hp} = \begin{bmatrix} 120.545 \\ 803.957 \\ 2485.669 \\ 6743.82 \\ 15571.309 \\ 27247.044 \\ 67153.448 \end{bmatrix}$

$C_{SD} := .28$

appendage: $P_{EAPP_i} := \left(LWL \cdot D_P \cdot C_{DAPP} + .5 \cdot C_{SD} \cdot \rho_{SW} \cdot A_{SD}\right) \cdot \left(V_i\right)^3$ $\qquad \frac{P_{EAPP}}{hp} = \begin{bmatrix} 101.866 \\ 814.929 \\ 2750.387 \\ 6519.436 \\ 12733.273 \\ 16040.256 \\ 34940.1 \end{bmatrix}$

air: $P_{EAA_i} := .5 \cdot C_{AA} \cdot A_W \cdot \rho_A \cdot \left(V_i\right)^3$

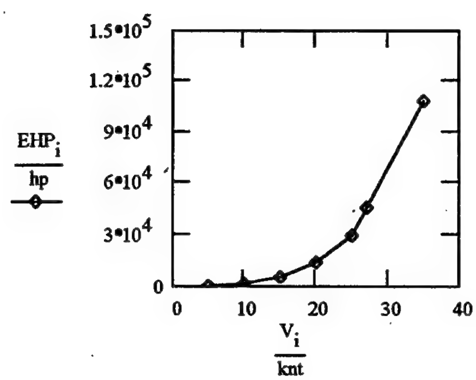
$$\frac{P_{EAA}}{hp} = \begin{bmatrix} 3.27 \\ 26.163 \\ 88.3 \\ 209.304 \\ 408.797 \\ 514.966 \\ 1121.738 \end{bmatrix}$$

$P_{ET_i} := P_{EBH_i} + P_{EAPP_i} + P_{EAA_i}$ $\qquad \frac{P_{ET}}{hp} = \begin{bmatrix} 225.681 \\ 1645.049 \\ 5324.356 \\ 13472.559 \\ 28713.378 \\ 43802.266 \\ 103215.286 \end{bmatrix}$

$EHP_i := PMF \cdot P_{ET_i}$

$\frac{V_i}{knt}$ = 5, 10, 15, 20, 25, 27, 35

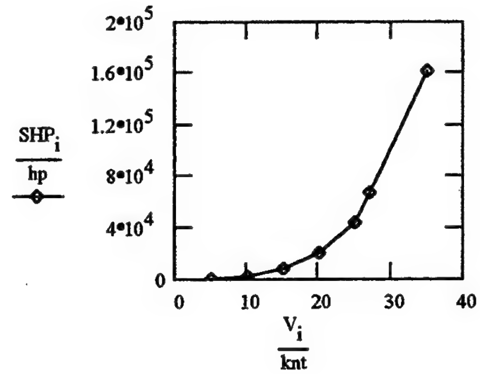
$$EHP = \begin{bmatrix} 236.965 \\ 1727.302 \\ 5590.573 \\ 14146.187 \\ 30149.047 \\ 45992.38 \\ 108376.051 \end{bmatrix} hp$$



III4. Shaft Horsepower:

Approximate Propulsive Coeficient (PC): $PC := .67$ $SHP_i := \dfrac{EHP_i}{PC}$

$$SHP = \begin{bmatrix} 353.68 \\ 2578.062 \\ 8344.139 \\ 21113.712 \\ 44998.578 \\ 68645.343 \\ 161755.299 \end{bmatrix} \cdot hp$$



Endurance Shaft Horsepower: $P_e := SHP_4$ $P_e = 21113.712 \cdot hp$

Sustained Speed Installed Shaft Horsepower Required (Allows for fouling and sea state):

$P_S := SHP_6$ $P_S = 68645.343 \cdot hp$ $P_{IREQ} := 1.25 \cdot P_S$ $P_{IREQ} = 85806.678 \cdot hp$

Actual installed SHP must be greater than P $_{IREQ}$

$P_{IBRAKE} := N_{PENG} \cdot P_{BPENG}$ $P_{IBRAKE} = 105800 \cdot hp$ $\eta := .97$ $P_I := \eta \cdot P_{IBRAKE}$ $P_I = 102626 \circ$

(P_I must be > P_{IREQ}) $P_{IREQ} = 85806.678 \cdot hp$ $ERR_{POWER} := \dfrac{P_I - P_{IREQ}}{P_{IREQ}}$ $ERR_{POWER} = 0.196$ **##ck**

III5. Estimate Propulsion Fuel Required:
Reference: DDS 200-1 "Calculate of Surface Ship Endurance Fuel"

Average Endurance Brake SHP Required (Allows for fouling and sea state):

$$P_{eBAVG} := 1.1 \cdot \frac{P_e}{\eta} \qquad P_{eBAVG} = 23943.385 \cdot hp$$

Specific fuel rate for propulsion engines:
(GT; FR for diesel = .327)

$$FR := 1.97 \cdot \frac{lb}{hp^{.85} \cdot hr} \cdot P_{eBAVG}^{-.15} \qquad FR = 0.434 \circ \frac{lb}{hp \cdot hr} \quad \#$$

(for ICR: FR=.347 lb/hphr)

Margin for instrumentation and machinery differences, f(P_e/P_I): $f_1 := 1.04$

Specified fuel rate: $FR_{SP} := f_1 \cdot FR$

Average fuel rate allowing for plant deterioration:

$$FR_{AVG} := 1.05 \cdot FR_{SP} \qquad FR_{AVG} = 0.474 \circ \frac{lb}{hp \cdot hr}$$

Burnable propulsion endurance fuel weight:

$$W_{BP} := \frac{E}{V_e} \cdot \left(P_{eBAVG} \cdot FR_{AVG}\right) \qquad W_{BP} = 1900.115 \circ lton$$

Tailpipe allowance and propulsion endurance fuel: $TPA := .95$ **(shallow tanks)**

$$W_{FP} := \frac{W_{BP}}{TPA} \qquad W_{FP} = 2000.121 \cdot lton$$

Allow for expansion and tank structure in required propulsion tank volume:

$$\gamma_F := 43 \cdot \frac{ft^3}{lton} \qquad V_{FP} := 1.02 \cdot 1.05 \cdot \gamma_F \cdot W_{FP} \qquad V_{FP} = 92111.562 \cdot ft^3$$

III6. Estimate electric load.

Reference: DDS 310-1

Estimate Maximum Functional Load based on parametrics for WINTER cruise condition:

Propulsion: $kW_P := .00466 \cdot \frac{kW}{hp} \cdot P_{IBRAKE}$ $\qquad kW_P = 493.028 \cdot kW$

Steering: $kW_S := .00583 \cdot \frac{kW}{ft^2} \cdot LWL \cdot T$ $\qquad kW_S = 59.416 \cdot kW$

Lighting: $kW_L := .0002053 \cdot \frac{kW}{ft^3} \cdot 1.8 \cdot LWL \cdot T \cdot B$ $\qquad kW_L = 234.419 \cdot kW$

Miscellaneous: $kW_M := 46.1 \cdot kW$

Heating: $kW_H := .0013 \cdot \frac{kW}{ft^3} \cdot 1.25 \cdot LWL \cdot T \cdot B$ $\qquad kW_H = 1030.826 \cdot kW$

(zero if no CPS)

Ventilation: $kW_{CPS} := .00026 \cdot \frac{kW}{ft^3} \cdot 1.8 \cdot LWL \cdot T \cdot B$ $\qquad kW_{CPS} = 296.878 \cdot kW$

$kW_V := .19 \cdot (kW_H + kW_P) + kW_{CPS}$ $\qquad kW_V = 586.41 \cdot kW$

Air Conditioning: $kW_{AC} := .67 \cdot \left(.1 \cdot kW \cdot N_T + .0015 \cdot \frac{kW}{ft^3} \cdot .47 \cdot 1.3 \cdot LWL \cdot T \cdot B + .1 \cdot kW_P\right)$

$kW_{AC} = 432.611 \cdot kW$

Aux Boiler and FW:
(electric boiler) $kW_B := .94 \cdot N_T \cdot kW$ $\qquad kW_B = 141 \cdot kW$

Firemain: $kW_F := .0001 \cdot \frac{kW}{ft^3} \cdot 1.8 \cdot LWL \cdot T \cdot B$ $\qquad kW_F = 114.184 \cdot kW$

Unrep and handling: $kW_{RH} := .00002 \cdot \frac{kW}{ft^3} \cdot 1.25 \cdot LWL \cdot T \cdot B$ $\qquad kW_{RH} = 15.859 \cdot kW$

Aux Machinery: $kW_A := .22 \cdot N_T \cdot kW + kW_{fins}$ $\quad kW_A = 33 \cdot kW$

Services and Work Spaces: $kW_{SERV} := .35 \cdot N_T \cdot kW$ $\quad kW_{SERV} = 52.5 \cdot kW$

Non-Payload Functional Load:

$$kW_{NP} := kW_P + kW_S + kW_L + kW_M + kW_H + kW_V + kW_{AC} + kW_B + kW_F + kW_{RH} + kW_A + kW_{SER}$$

Maximum Functional Load:

$kW_{MFL} := kW_{PAY} + kW_{NP}$ $\quad kW_{MFL} = 3779.423 \cdot kW$

MFL with margins: (design,growth):

$kW_{MFLM} := 1.2 \cdot 1.2 \cdot kW_{MFL}$ $\quad kW_{MFLM} = 5442.37 \cdot kW$

Installed Electrical Power Required:

Power available per generator: $kW_G = 3000 \cdot kW$

Power required per generator: $kW_{GREQ} := \dfrac{kW_{MFLM}}{(N_G - 1) \cdot .9}$ $\quad kW_{GREQ} = 3023.539 \cdot kW$ $\quad$ #ck

$$ERR_{KW} := \frac{kW_G - kW_{GREQ}}{kW_{GREQ}}$$

24 hour electrical load:

$kW_{24} := .5 \cdot (kW_{MFL} - kW_P - kW_S) + .8 \cdot (kW_P + kW_S)$ $\quad kW_{24} = 2055.445 \cdot kW$

$ERR_{KW} = -0.008$

with margin (design): $kW_{24AVG} := 1.2 \cdot kW_{24}$ $\quad kW_{24AVG} = 2466.534 \cdot kW$

III7. Estimate Electric Fuel Rate: $FR_G = 0.113 \cdot \dfrac{lb}{kW \cdot hr}$

Margin for instrumentation and machinery differences, f(P$_e$/P$_I$): $f_{1e} := 1.04$

Specified fuel rate: $FR_{GSP} := f_{1e} \cdot FR_G$

Average fuel rate allowing for plant deterioration:

$FR_{GAVG} := 1.05 \cdot FR_{GSP}$ $\quad FR_{GAVG} = 0.124 \cdot \dfrac{lb}{kW \cdot hr}$ $\quad FR_{GAVG} = 0.092 \cdot \dfrac{lb}{hp \cdot hr}$

III8. Estimate Electrical and Total fuel Required

Burnable electrical endurance fuel weight:

$W_{Be} := \dfrac{E}{V_e} \cdot (kW_{24AVG} \cdot FR_{GAVG})$ $\quad W_{Be} = 51.127 \cdot lton$

$TPA := .95$
(shallow tanks)

Tailpipe allowance and electrical endurance fuel:

$W_{Fe} := \dfrac{W_{Be}}{TPA}$ $\quad W_{Fe} = 53.818 \cdot lton$

Allow for expansion and tank structure in required electrical fuel tank volume:

$$V_{Fe} := 1.02 \cdot 1.05 \cdot \gamma_F \cdot W_{Fe} \qquad V_{Fe} = 2478.484 \cdot ft^3$$

Total ship fuel: (DFM)

$$W_{F41} := W_{FP} + W_{Fe} \qquad W_{F41} = 2053.939 \cdot lton$$

$$V_F := V_{FP} + V_{Fe} \qquad V_F = 94590.046 \cdot ft^3$$

IV. Space Estimate

IVA. Available Space

IVA1. Underwater Hull Volume Available

$$V_{HUW} := V_{FL} \qquad V_{HUW} = 290058.58 \cdot ft^3$$

IVA2. Sheer Line. (3 criteria)

1) Keep deck edge above water at 25 degree heel

2) Longitudinal strength

3) Contain machinery box height: $H_{MBMIN} = 22 \cdot ft$

$$M := \begin{bmatrix} .21 \cdot B + T \\ \dfrac{LWL}{15} \\ H_{MBMIN} \end{bmatrix} \qquad M = \begin{bmatrix} 32.223 \\ 35.475 \\ 22 \end{bmatrix} \cdot ft \qquad D_{10MIN} := \max(M) \qquad D_{10MIN} = 35.475 \cdot ft$$

#ck

$$D_{10} := D_{10MIN} + 1 \cdot ft$$

$$D_{0MIN} := 1.011827 \cdot T - 6.36215 \cdot \frac{10^{-6}}{ft} \cdot LWL^2 + 2.780649 \cdot 10^{-2} \cdot LWL + T \qquad D_{0MIN} = 51.526 \cdot ft \qquad D_0 := D_{0MIN}$$

$$D_{20MIN} := .014 \cdot LWL \cdot \left(2.125 + 1.25 \cdot \frac{10^{-3}}{ft} \cdot LWL\right) + T \qquad D_{20MIN} = 39.938 \cdot ft \qquad D_{20} := D_{20MIN}$$

IVA3. Above-Water Hull Volume

$$F_0 := D_0 - T \qquad F_{10} := D_{10} - T \qquad F_{20} := D_{20} - T$$

$$A_{PRO} := LWL \cdot \frac{F_0 + 4 \cdot F_{10} + F_{20}}{6} \qquad F_{AV} := \frac{A_{PRO}}{LWL} \qquad F_{AV} = 20.409 \cdot ft$$

$$D_{AV} := F_{AV} + T \qquad D_{AV} = 39.561 \cdot ft$$

cubic #: $CN := \dfrac{LWL \cdot B \cdot D_{AV}}{10^5 \cdot ft^3} \qquad CN = 13.103$

$$C_W := .236 + .836 \cdot C_P \qquad C_W = 0.729$$

flare factor: $f_f := .714599 + .18098 \cdot \dfrac{D_{AV}}{T} - .018828 \cdot \left(\dfrac{D_{AV}}{T}\right)^2 \qquad M_f := \begin{bmatrix} f_f \\ 1 \end{bmatrix} \qquad f_f := \max(M_f)$

$$f_f = 1.008$$

$$V_{HAW} := LWL \cdot B \cdot F_{AV} \cdot C_W \cdot f_f \qquad V_{HAW} = 496947.294 \cdot ft^3$$

IVA4. Total Hull Volume.

$$V_{HT} := V_{HUW} + V_{HAW} \qquad V_{HT} = 787005.874 \cdot ft^3$$

IVA5. Size Deck House:

$$V_{DMAX} := .0025 \cdot LWL^3 \qquad V_{DMAX} = 376699.455 \cdot ft^3$$

$$V_{DMIN} := .0005 \cdot LWL^3 \qquad V_{DMIN} = 75339.891 \cdot ft^3 \qquad V_D = 190000 \cdot ft^3$$ #ck

IVA6. Calculate Total Ship Volume

$$V_T := V_{HT} + V_D \qquad V_T = 977005.874 \cdot ft^3$$

IVB. Space Requirement

IVB1. Machinery Box **(assumed near midships)** $B_{MB} := B \quad B_{MB} = 62.244 \cdot ft$

$$H_{MB} := D_{10} \qquad L_{MB} = 40 \cdot ft \qquad A_{MB} := B \cdot T \cdot C_X + B \cdot (H_{MB} - T) \qquad A_{MB} = 2002.156 \cdot ft^2$$

Calculate Machinery Box Volume:

$$V_{MB} := L_{MB} \cdot A_{MB} \cdot C_{PMB} \qquad V_{MB} = 79926.062 \cdot ft^3 \qquad V_{AUX} := 1.2 \cdot V_{MB} \qquad V_{AUX} = 95911.274 \cdot ft^3$$

IVB2. Tankage

Helo:

Helo fuel weight from Payload Spreadsheet: $W_{F42} = 63.8 \cdot lton$

Allow for tank structure and expansion: $\gamma_{HF} := 43 \cdot \dfrac{ft^3}{lton}$

$$V_{HF} := 1.02 \cdot 1.05 \cdot W_{F42} \cdot \gamma_{HF} \qquad V_{HF} = 2938.181 \cdot ft^3$$

Lube Oil:

LO weight: $W_{F46} := 7.2 \cdot lton$

Allow for tank structure and expansion: $\gamma_{LO} := 39 \cdot \dfrac{ft^3}{lton}$

$$V_{LO} := 1.02 \cdot 1.05 \cdot W_{F46} \cdot \gamma_{LO} \qquad V_{LO} = 300.737 \cdot ft^3$$

Potable Water:

Water weight: $W_{F52} := N_T \cdot .15 \cdot lton \qquad W_{F52} = 22.5 \cdot lton$

Allow for tank structure: $\gamma_W := 36 \cdot \dfrac{ft^3}{lton}$

$$V_W := 1.02 \cdot W_{F52} \cdot \gamma_W \qquad V_W = 826.2 \cdot ft^3$$

Sewage: $V_{SEW} := N_T \cdot 2 \cdot ft^3 \qquad V_{SEW} = 300 \cdot ft^3$

Waste Oil: $V_{WASTE} := .005 \cdot V_{FL} \qquad V_{WASTE} = 1450.293 \cdot ft^3$

Clean Balast: $V_{BAL} := .032 \cdot V_{FL} \qquad V_{BAL} := 0 \cdot ft^3 \qquad V_{BAL} = 0 \cdot ft^3$

(for compensated system)

Total:

$$V_{TK} := V_F + V_{HF} + V_{LO} + V_W + V_{SEW} + V_{WASTE} + V_{BAL} \qquad V_{TK} = 100405.457 \cdot ft^3$$

IVB3. Payload Deck Areas

Deckhouse payload area: (including access) $A_{DPR} := 1.15 \cdot A_{DPA} + 1.23 \cdot A_{DPC}$ $A_{DPR} = 10143.981 \cdot ft^2$

Hull payload area: (including access) $A_{HPR} := 1.15 \cdot A_{HPA} + 1.23 \cdot A_{HPC}$ $A_{HPR} = 9797.796 \cdot ft^2$

IVB4. Living Deck Area

Deckhouse: $A_{COXO} := 225 \cdot ft^2$ $A_{DO} := 75 \cdot N_O \cdot ft^2$ $A_{DO} = 1125 \cdot ft^2$

$A_{DL} := A_{COXO} + A_{DO}$ $A_{DL} = 1350 \cdot ft^2$

Hull: $A_{HAB} := 50 \cdot ft^2$ $A_{HL} := \left(A_{HAB} + \frac{LWL}{100} \cdot ft\right) \cdot N_T - A_{DL}$

$A_{HL} = 6948.196 \cdot ft^2$

IVB5. Hull Stores

$A_{HS} := 300 \cdot ft^2 + .0158 \cdot \frac{ft^2}{lb} \cdot N_T \cdot 9 \cdot \frac{lb}{day} \cdot T_S$ $A_{HS} = 1259.85 \cdot ft^2$

IVB6. Other Ship Functions

Deckhouse:

Maintenance:

$A_{DM} := .05 \cdot \left(A_{DPR} + A_{DL}\right)$ $A_{DM} = 574.699 \cdot ft^2$

Bridge and Chartroom:

$A_{DB} := 16 \cdot ft \cdot (B - 18 \cdot ft)$ $A_{DB} = 707.906 \cdot ft^2$

Engine Inlet/Exhaust:

$A_{DIE} := 1.4 \cdot N_{DIE} \cdot \left(A_{PIE} + A_{eIE}\right)$ $A_{DIE} = 918.4 \cdot ft^2$

Hull:

Ship Functions:

$A_{HSF} := 2500 \cdot ft^2 \cdot CN$ $A_{HSF} = 32758.449 \cdot ft^2$

Engine Inlet/Exhaust:

$A_{HIE} := 1.4 \cdot \left(N_{HPIE} \cdot A_{PIE} + N_{HeIE} \cdot A_{eIE}\right)$ $A_{HIE} = 161.28 \cdot ft^2$

IVB7. Total Required Area and Volume

Hull:

$A_{HR} := A_{HPR} + A_{HL} + A_{HS} + A_{HSF} + A_{HIE}$ $A_{HR} = 50925.571 \cdot ft^2$

$V_{HR} := H_{DK} \cdot A_{HR}$ $V_{HR} = 458330.139 \cdot ft^3$

Deckhouse:

$A_{DR} := A_{DPR} + A_{DL} + A_{DM} + A_{DB} + A_{DIE}$ $A_{DR} = 13694.986 \cdot ft^2$

$V_{DR} := H_{DK} \cdot A_{DR}$ $V_{DR} = 123254.878 \cdot ft^3$

Total:

$A_{TR} := A_{HR} + A_{DR}$ $\quad A_{TR} = 64620.557 \cdot ft^2$

$V_{TR} := H_{DK} \cdot A_{TR}$ $\quad V_{TR} = 581585.017 \cdot ft^3$

IVC. Space Balance

$V_D = 190000 \cdot ft^3$ $\quad V_{DR} = 123254.878 \cdot ft^3$

$V_{HA} := V_{HT} - V_{MB} - V_{AUX} - V_{TK}$ $\quad V_{HA} = 510763.081 \cdot ft^3$ $\quad V_{HR} = 458330.139 \cdot ft^3$

$V_{TA} := V_{HA} + V_D$ $\quad V_{TA} = 700763.081 \cdot ft^3 \quad > \quad V_{TR} = 581585.017 \cdot ft^3$ #ck

$A_{HA} := \dfrac{V_{HA}}{H_{DK}}$ $\quad A_{HA} = 56751.453 \cdot ft^2$ $\quad A_{HR} = 50925.571 \cdot ft^2$

$A_{DA} := \dfrac{V_D}{H_{DK}}$ $\quad A_{DA} = 21111.111 \cdot ft^2$ $\quad A_{DR} = 13694.986 \cdot ft^2$

$A_{TA} := A_{DA} + A_{HA}$ $\quad A_{TA} = 77862.565 \cdot ft^2 \quad > \quad A_{TR} = 64620.557 \cdot ft^2$ #ck

$ERR_{VOL} := \dfrac{V_{TA} - V_{TR}}{V_{TR}}$ $\quad ERR_{VOL} = 0.204919$ $\qquad ERR_{AREA} := \dfrac{A_{TA} - A_{TR}}{A_{TR}}$ $\quad ERR_{AREA} = 0.204919$

V. Weight

V1. Propulsion (200)

Basic Machinery: (230+241/242+ 250-290) $\quad W_{BM} := P_I \cdot \dfrac{lb}{hp} \cdot \left[9.0 + 12.4 \cdot \left(P_I \cdot \dfrac{10^{-5}}{hp} - 1 \right)^2 \right]$ $\quad W_{BM} = 412.728 \cdot lton$

Shafting: (243) $\quad f_S := .5 \quad W_S := .356 \cdot \dfrac{lton}{ft} \cdot LWL \cdot f_S$ $\quad W_S = 94.719 \cdot lton$

(f_S=.5 for twin screws)

Props: (245) $\quad W_{PR} := .05575 \cdot lb \cdot \left(\dfrac{D_P}{ft} \right)^{5.497 - \frac{.0433}{ft} \cdot D_P} \cdot N_P$ $\quad W_{PR} = 47.599 \cdot lton$

Bearings: (244) $\quad W_B := .15 \cdot (W_S + W_{PR})$ $\quad W_B = 21.348 \cdot lton$

Total Shafting: $\quad W_{ST} := W_S + W_B + W_{PR}$ $\quad W_{ST} = 163.666 \cdot lton$

Total Propulsion: $\quad W_2 := W_{BM} + W_{ST} + W_{237}$ $\quad W_2 = 576.394 \cdot lton$

V2. Electrical Plant (300)

$W_3 := 50 \cdot lton + .03214 \cdot \dfrac{lton}{kW} \cdot N_G \cdot kW_G$ $\quad W_3 = 339.26 \cdot lton$

V3. Command/Control/Surveillance (400)

Gyro/IC/Navigation (420, 430): $W_{IC} := 4.65 \cdot CN \cdot lton$ $\qquad W_{IC} = 60.931 \, lton$

Other/Misc Group 400: $W_{CO} := 2.24 \cdot CN \cdot lton$ $\qquad W_{CO} = 29.352 \, lton$

Cabling: $W_{CC} := .04 \cdot (W_{P400} + W_{IC} + W_{CO})$ $\qquad W_{CC} = 9.537 \, lton$

$$W_4 := W_{P400} + W_{IC} + W_{CO} + W_{CC} + W_{498} \qquad W_4 = 335.859 \, lton$$

V4. Auxiliary Systems (500)

aux steam (electric aux boiler): **hotel steam:** $Q_{HS} := 15 \cdot N_T$ **distiller:** $Q_{DS} := 6.5 \cdot N_T + 250$

$W_{517} := .0013 \cdot (Q_{HS} + Q_{DS}) \cdot lton$ $\qquad W_{517} = 4.518 \, lton$ **aux sys operating fluids:** $W_{598} := .000075 \cdot V_T \cdot \frac{lton}{ft^3}$

$W_{598} = 73.275 \, lton$

$$W_{AUX} := \left[.000772 \cdot \left(\frac{V_T}{ft^3} \right)^{1.443} + 5.14 \cdot \frac{V_T}{ft^3} + 6.19 \cdot \left(\frac{V_T}{ft^3} \right)^{.7224} + 377 \cdot N_T + 2.74 \cdot \frac{P_I}{hp} \right] \cdot 10^{-4} \cdot lton + 113.8 \cdot lton$$

environmental support: $W_{593} := 10 \cdot lton$ $\qquad W_5 := W_{AUX} + W_{P500} + W_{517} + W_{593} + W_{598} + W_{CPS}$

$W_5 = 862.05 \, lton$

V5. Outfit & Furnishings (600)

Hull Fittings: $W_{OFH} := \left(31.4 + \frac{.0003187}{ft^3} \cdot V_T \right) \cdot lton$ $\qquad W_{OFH} = 342.772 \, lton$

Personnel-related: $W_{OFP} := .8 \cdot (N_T - 9.5) \cdot lton$ $\qquad W_{OFP} = 112.4 \, lton$

$$W_6 := W_{OFP} + W_{OFH} + W_{P600} \qquad W_6 = 462.912 \, lton$$

V6. Structure (100)

Hull (110-140, 160, 190): $W_{BH} := C_{HMAT} \cdot (1.68341 \cdot CN^2 + 167.1721 \cdot CN - 103.283) \cdot lton$ $\qquad W_{BH} = 2209.936 \, lton$

$$\rho_{DH} := \text{if}(C_{DHMAT} = 1, .0007, .001429) \qquad \rho_{DH} = 0.001$$

Deckhouse (150): $W_{DH} := \rho_{DH} \cdot \frac{lton}{ft^3} \cdot V_D$ $\qquad W_{DH} = 271.51 \, lton$

Masts: $W_{171} := .0688 \cdot \frac{lton}{ft} \cdot LWL - 13.75 \cdot lton$ $\qquad W_{171} = 22.861 \, lton$

Foundations: $W_{180} := .0675 \cdot W_{BM} + .072 \cdot (W_3 + W_4 + W_5 + W_7)$ $\qquad W_{180} = 146.986 \, lton$

$$W_1 := W_{BH} + W_{DH} + W_{171} + W_{180} + W_{165} + W_{164} \qquad W_1 = 2736.993 \, lton$$

V7. Single Digit Weight Summary & Weight Balance: $i1 := 1, 2 .. 7$

Weight margin: (Future Growth) $W_{M24} := .1 \cdot \left(\sum_{i1} W_{i1} \right)$ $W_{M24} = 543.084 \cdot lton$

Lightship:

$$W_{LS} := \sum_{i1} W_{i1} + W_{M24} \qquad W_{LS} = 5973.922 \cdot lton$$

Additional Loads:

Provisions: $W_{F31} := N_T \cdot 9 \cdot \frac{lb}{day} \cdot T_S$ $W_{F31} = 27.121 \cdot lton$

General stores: $W_{F32} := .0009598 \cdot \frac{lton}{day} \cdot T_S \cdot N_T$ $W_{F32} = 6.479 \cdot lton$

Crew: $W_{F10} := 236 \cdot lb \cdot N_E + 400 \cdot lb \cdot \left(N_O + 1 \right)$ $W_{F10} = 17.08 \cdot lton$

$$W_T := W_{LS} + W_{F41} + W_{F42} + W_{F20} + W_{F46} + W_{F52} + W_{F31} + W_{F32} + W_{F10}$$

$W_T = 8359.5 \cdot lton$

Weight Balance: $ERR_{WEIGHT} := \frac{\Delta_{FL} - W_T}{W_T}$

$ERR_{WEIGHT} = -0.008626$ #ck

VI. Stability

VI1. Calculate Light Ship Weight Group Moments:

Weight	VCG		Product
$W_{BH} = 2209.936 \cdot lton$	$VCG_1 := .527 \cdot D_{10}$	$VCG_1 = 19.223 \cdot ft$	$P_1 := W_{BH} \cdot VCG_1$
$W_{DH} = 271.51 \cdot lton$	$VCG_2 := D_{10} + 1.5 \cdot H_{DK}$	$VCG_2 = 49.975 \cdot ft$	$P_2 := W_{DH} \cdot VCG_2$
$W_{180} = 146.986 \cdot lton$	$VCG_3 := .68 \cdot D_{10}$	$VCG_3 = 24.803 \cdot ft$	$P_3 := W_{180} \cdot VCG_3$
$W_{171} = 22.861 \cdot lton$	$VCG_4 := 2.65 \cdot D_{10}$	$VCG_4 = 96.66 \cdot ft$	$P_4 := W_{171} \cdot VCG_4$

$$P_{100} := P_1 + P_2 + P_3 + P_4 \qquad VCG_{100} := \frac{P_{100}}{W_1} \qquad VCG_{100} = 22.618 \cdot ft$$

$W_{BM} = 412.728 \cdot lton$	$VCG_5 := .5 \cdot D_{10}$	$VCG_5 = 18.238 \cdot ft$	$P_5 := W_{BM} \cdot VCG_5$
$W_{ST} = 163.666 \cdot lton$	$VCG_6 := 3.9 \cdot ft + .19 \cdot T$	$VCG_6 = 7.539 \cdot ft$	$P_6 := W_{ST} \cdot VCG_6$
$W_{237} = 0 \cdot lton$	$VCG_7 := VCG_{237}$	$VCG_7 = 0 \cdot ft$	$P_7 := W_{237} \cdot VCG_7$

$$P_{200} := P_5 + P_6 + P_7 \qquad VCG_{200} := \frac{P_{200}}{W_2} \qquad VCG_{200} = 15.2 \cdot ft$$

$W_3 = 339.26 \cdot lton$	$VCG_8 := .65 \cdot D_{10}$	$VCG_8 = 23.709 \cdot ft$	$P_8 := W_3 \cdot VCG_8$
$W_{IC} = 60.931 \cdot lton$	$VCG_9 := D_{10}$	$VCG_9 = 36.475 \cdot ft$	$P_9 := W_{IC} \cdot VCG_9$
$W_{CO} = 29.352 \cdot lton$	$VCG_{10} := 5.6 \cdot ft + .4625 \cdot D_{10}$	$VCG_{10} = 22.47 \cdot ft$	$P_{10} := W_{CO} \cdot VCG_{10}$
$W_{CC} = 9.537 \cdot lton$	$VCG_{11} := .5 \cdot D_{10}$	$VCG_{11} = 18.238 \cdot ft$	$P_{11} := W_{CC} \cdot VCG_{11}$
$W_{498} = 87.9 \cdot lton$	$VCG_{12} := VCG_{498}$	$VCG_{12} = -1.2 \cdot ft$	$P_{12} := W_{498} \cdot VCG_{12}$
$W_{AUX} = 696.867 \cdot lton$	$VCG_{13} := .9 \cdot (D_{10} - 7.4 \cdot ft)$	$VCG_{13} = 26.168 \cdot ft$	$P_{13} := W_{AUX} \cdot VCG_{13}$
$W_{517} = 4.518 \cdot lton$	$VCG_{14} := .5 \cdot H_{MB}$	$VCG_{14} = 18.238 \cdot ft$	$P_{14} := W_{517} \cdot VCG_{14}$
$W_{OFH} = 342.772 \cdot lton$	$VCG_{15} := .805 \cdot D_{10}$	$VCG_{15} = 29.363 \cdot ft$	$P_{15} := W_{OFH} \cdot VCG_{15}$
$W_{OFP} = 112.4 \cdot lton$	$VCG_{16} := 8 \cdot ft + .71 \cdot D_{10}$	$VCG_{16} = 33.898 \cdot ft$	$P_{16} := W_{OFP} \cdot VCG_{16}$

$ip := 1 .. 16$

$$P_{WG} := \sum_{ip} P_{ip} + W_P \cdot VCG_P - W_{VP} \cdot VCG_{VP} \qquad P_{WG} = 122974.982 \cdot lton \cdot ft$$

VI2. Light Ship KG

$$VCG_{LS} := \frac{P_{WG}}{\sum_{i1} W_{i1}} \qquad VCG_{LS} = 22.644 \cdot ft \qquad KG_{LS} := VCG_{LS} \qquad KG_{LS} = 22.644 \cdot ft$$

VI3. Calculate Variable Load Weight Group Moments:

Weight	VCG		Product
$W_{F10} = 17.08 \cdot lton$	$VCG_{17} := .746 \cdot D_{10}$	$VCG_{17} = 27.211 \cdot ft$	$P_{17} := W_{F10} \cdot VCG_{17}$
$W_{F31} = 27.121 \cdot lton$	$VCG_{18} := .55 \cdot D_{10}$	$VCG_{18} = 20.061 \cdot ft$	$P_{18} := W_{F31} \cdot VCG_{18}$
$W_{F32} = 6.479 \cdot lton$	$VCG_{19} := .65 \cdot D_{10}$	$VCG_{19} = 23.709 \cdot ft$	$P_{19} := W_{F32} \cdot VCG_{19}$
$W_{F41} = 2053.939 \cdot lton$	$VCG_{20} := 7.5 \cdot ft$	$VCG_{20} = 7.5 \cdot ft$	$P_{20} := W_{F41} \cdot VCG_{20}$
$W_{F42} = 63.8 \cdot lton$	$VCG_{21} := 10. \cdot ft$	$VCG_{21} = 10 \cdot ft$	$P_{21} := W_{F42} \cdot VCG_{21}$
$W_{F46} = 7.2 \cdot lton$	$VCG_{22} := .35 \cdot D_{10}$	$VCG_{22} = 12.766 \cdot ft$	$P_{22} := W_{F46} \cdot VCG_{22}$
$W_{F52} = 22.5 \cdot lton$	$VCG_{23} := 7.5 \cdot ft$	$VCG_{23} = 7.5 \cdot ft$	$P_{23} := W_{F52} \cdot VCG_{23}$

$$iL := 17..23 \qquad P_{WGL} := \sum_{iL} P_{iL} + W_{VP} \cdot VCG_{VP} \qquad P_{WGL} = 24906.211 \cdot lton \cdot ft$$

$$W_L := W_{F41} + W_{F42} + W_{F20} + W_{F46} + W_{F52} + W_{F31} + W_{F32} + W_{F10} \qquad W_L = 2385.578 \cdot lton$$

$$VCG_L := \frac{P_{WGL}}{W_L} \qquad VCG_L = 10.44 \cdot ft$$

VI4. Calculate Ship Stability Characteristics:

$$KG_{MARG} := .5 \cdot ft \quad KG := \frac{W_{LS} \cdot KG_{LS} + W_L \cdot VCG_L}{W_T} + KG_{MARG} \quad C_{IT} := -.497 + 1.44 \cdot C_W \quad C_{IT} = 0.553$$

$$KB := \frac{T}{3} \cdot \left(2.5 - \frac{C_P \cdot C_X}{C_W} \right) \quad BM := \frac{LWL \cdot B^3 \cdot C_{IT}}{12 \cdot V_{FL}} \quad GM := KB + BM - KG \quad C_{GMB} := \frac{GM}{B}$$

$$KG = 19.661 \cdot ft \quad KB = 11.957 \cdot ft \quad BM = 20.392 \cdot ft \quad GM = 12.688 \cdot ft \quad C_{GMB} = 0.204$$

#ck

$Mdol := coul$ $\qquad Kdol := \frac{Mdol}{1000}$

$Bdol := 1000 \cdot Mdol$ $\qquad dol := \frac{Kdol}{1000}$

VII. VERY SIMPLIFIED COST MODEL (Lead-Ship End Cost only)

V!!1. Additional charcteristics:

Ship Service Life: $L_S := 30$ **Initial Operational Capability:** $Y_{IOC} := 1998$ #

Total Ship Acquisition: $N_S := 25$ **Production Rate (per year):** $R_P := 3$ #

Inflation:

Base Year: $Y_B := 1998$ $\quad iy := 1 .. Y_B - 1981$

Average Inflation Rate (%): $R_I := 5.$
(from 1981)

$$F_I := \prod_{iy} \left(1 + \frac{R_I}{100}\right) \qquad F_I = 2.292$$

a. Lead Ship Cost - Shipbuilder Portion:

SWBS costs: (See Table 5 for K_N factors)

Structure $K_{N1} := \frac{.55 \cdot Mdol}{lton^{.772}}$ $\quad C_{L_1} := .03395 \cdot F_I \cdot K_{N1} \cdot (W_1)^{.772}$ $\quad C_{L_1} = 19.275 \cdot Mdol$

+ Propulsion $K_{N2} := \frac{1.2 \cdot Mdol}{hp^{.808}}$ $\quad C_{L_2} := .00186 \cdot F_I \cdot K_{N2} \cdot P_{IBRAKE}^{.808}$ $\quad C_{L_2} = 58.708 \cdot Mdol$

+ Electric $K_{N3} := \frac{1.0 \cdot Mdol}{lton^{.91}}$ $\quad C_{L_3} := .07505 \cdot F_I \cdot K_{N3} \cdot (W_3)^{.91}$ $\quad C_{L_3} = 34.542 \cdot Mdol$

+ Command, Control, Surveillance

$K_{N4} := \frac{2.0 \cdot Mdol}{lton^{.617}}$ $\quad C_{L_4} := .10857 \cdot F_I \cdot K_{N4} \cdot (W_4)^{.617}$ $\quad C_{L_4} = 18.013 \cdot Mdol$

(less payload GFM cost)

+ Auxiliary $K_{N5} := \frac{1.5 \cdot Mdol}{lton^{.782}}$ $\quad C_{L_5} := .09487 \cdot F_I \cdot K_{N5} \cdot (W_5)^{.782}$ $\quad C_{L_5} = 64.421 \cdot Mdol$

+ Outfit $K_{N6} := \frac{1.0 \cdot Mdol}{lton^{.784}}$ $\quad C_{L_6} := .09859 \cdot F_I \cdot K_{N6} \cdot (W_6)^{.784}$ $\quad C_{L_6} = 27.784 \cdot Mdol$

+ Armament $K_{N7} := \frac{1.0 \cdot Mdol}{lton^{.987}}$ $\quad C_{L_7} := .00838 \cdot F_I \cdot K_{N7} \cdot (W_7)^{.987}$ $\quad C_{L_7} = 2.119 \cdot Mdol$

(Less payload GFM cost)

+ Margin Cost:

$$C_{LM} := \frac{W_{M24}}{\left(W_{LS} - W_{M24}\right)} \cdot \left(\sum_{i1} C_{L_{i1}}\right) \qquad C_{LM} = 22.486 \cdot Mdol$$

+ Integration/Engineering: (Lead ship includes detail design engineering for class)

$$K_{N8} := \frac{10.0 \cdot Mdol}{Mdol^{1.099}} \qquad C_{L_8} := .034 \cdot K_{N8} \cdot \left(\sum_{i1} C_{L_{i1}} + C_{LM}\right)^{1.099} \qquad C_{L_8} = 145.12 \cdot Mdol$$

+ Ship Assembly and Support: (Lead ship includes all tooling, jigs, special facilities for class)

$$K_{N9} := \frac{2.0 \cdot Mdol}{(Mdol)^{.839}} \qquad C_{L_9} := .135 \cdot K_{N9} \cdot \left(\sum_{i1} C_{L_{i1}} + C_{LM}\right)^{.839} \qquad C_{L_9} = 27.501 \cdot Mdol$$

= <u>Total Lead Ship Construction Cost: (BCC)</u> :

$$C_{LCC} := \sum_{i1} C_{L_{i1}} + C_{L_8} + C_{L_9} + C_{LM} \qquad C_{LCC} = 419.97 \cdot Mdol$$

+ Profit:

$$F_{PROFIT} := .10 \qquad C_{LP} := F_{PROFIT} \cdot C_{LCC} \qquad C_{LP} = 41.997 \cdot Mdol$$

= <u>Lead Ship Price</u> :

$$P_L := C_{LCC} + C_{LP} \qquad P_L = 461.967 \cdot Mdol$$

+ Change Orders:

$$C_{LCORD} := .12 \cdot P_L \qquad C_{LCORD} = 55.436 \cdot Mdol$$

= <u>Total Shipbuilder Portion:</u>

$$C_{SB} := P_L + C_{LCORD} \qquad C_{SB} = 517.403 \cdot Mdol$$

b. Lead Ship Cost - Government Portion

Other support: $C_{LOTH} := .025 \cdot P_L \qquad C_{LOTH} = 11.549 \cdot Mdol$

+ Program Manager's Growth: $C_{LPMG} := .1 \cdot P_L \qquad C_{LPMG} = 46.197 \cdot Mdol$

Costed Military Payload: $W_{MP} := W_4 + W_7 + W_{F20} - W_{IC} - W_{F23} \qquad W_{MP} = 567.028 \cdot lton$

+ Ordnance and Electrical GFE:
(Military Payload GFE)

$$C_{LMPG} := \left(.319 \cdot \frac{Mdol}{lton} \cdot W_{MP} + N_{HELO} \cdot 18.71 \cdot Mdol\right) \cdot F_I$$

$$C_{LMPG} = 500.352 \cdot Mdol$$

+ HM&E GFE (boats, IC): $C_{LHMEG} := .02 \cdot P_L$ $C_{LHMEG} = 9.239 \cdot Mdol$

+ Outfittimg Cost : $C_{LOUT} := .04 \cdot P_L$ $C_{LOUT} = 18.479 \cdot Mdol$

= <u>Total Government Cost:</u>

$C_{LGOV} := C_{LOTH} + C_{LPMG} + C_{LMPG} + C_{LHMEG} + C_{LOUT}$ $C_{LGOV} = 585.816 \cdot Mdol$

c. Total End Cost: (Must always be less than SCN appropriation)

*** <u>Total End Cost:</u>**

$C_{LEND} := C_{SB} + C_{LGOV}$ $C_{LEND} = 1103.22 \cdot Mdol$

SUMMARY: WITHOUT OPTIMIZATION

ITERATION WEIGHT: $W_{FL} \equiv 8287.388 \cdot \text{lton}$ $\quad$ $ERR_{WEIGHT} = -0.008626$ $\quad$ $V_{FL} \equiv W_{FL} \cdot 35 \cdot \frac{ft^3}{lton}$

$W_{FL1} = 6683 \cdot \text{lton}$ $\quad$ $W_T = 8359.5 \cdot \text{lton}$

GROSS CHARACTERISTICS:

$C_P \equiv .59$ **(.54 - .64)** $\quad$ $C_{\Delta L} \equiv 55 \cdot \frac{lton}{ft^3}$ **(45 - 65)** $\quad$ $LWL \equiv 100 \cdot \left(\frac{W_{FL}}{C_{\Delta L}}\right)^{\frac{1}{3}}$ $\quad$ $LWL = 532.131 \cdot ft$

$C_X \equiv .775$ **(.7 - .85)** $\quad$ $C_V := \frac{V_{FL}}{LWL^3}$ $\quad$ $C_V = 1.925 \cdot 10^{-3}$ $\quad$ $V_{FL} = 290058.58 \cdot ft^3$

$C_{BT} \equiv 3.25$ **(2.8 - 3.7)** $\quad$ $B \equiv \sqrt{\frac{C_{BT} \cdot V_{FL}}{C_P \cdot C_X \cdot LWL}}$ $\quad$ $B = 62.244 \cdot ft$ $\quad$ $T = 19.152 \cdot ft$ $\quad$ $C_{LB} = 8.549$ **(7.5 - 10)**

ENERGY BALANCE:

$V_S \equiv 27 \cdot \text{knt}$ $\quad$ $P_I = 102626 \cdot hp$ $\quad$ $P_{IREQ} = 85806.678 \cdot hp$ $\quad$ $ERR_{POWER} = 0.196$

$V_e \equiv 20 \cdot \text{knt}$ $\quad$ $kW_G = 3000 \cdot kW$ $\quad$ $kW_{GREQ} = 3023.539 \cdot kW$ $\quad$ $ERR_{KW} = -0.008$

$E \equiv 7500 \cdot \text{knt} \cdot \text{hr}$

AREA/VOLUME BALANCE:

$V_D \equiv 190000 \cdot ft^3$ $\quad$ $V_T = 977005.874 \cdot ft^3$ $\quad$ $V_{MB} = 79926.062 \cdot ft^3$ $\quad$ $V_{TR} = 581585.017 \cdot ft^3$

$V_{DMIN} = 75339.891 \cdot ft^3$ $\quad$ $V_{HT} = 787005.874 \cdot ft^3$ $\quad$ $V_{AUX} = 95911.274 \cdot ft^3$ $\quad$ $V_{TA} = 700763.081 \cdot ft^3$

$V_{DMAX} = 376699.455 \cdot ft^3$ $\quad$ $V_{TK} = 100405.457 \cdot ft^3$ $\quad$ $ERR_{AREA} = 0.204919$

$D_{10} = 36.475 \cdot ft$ **(Must be > D_{10MIN})**

$D_{10MIN} = 35.475 \cdot ft$

$A_{TR} = 64620.557 \cdot ft^2$ $\quad$ $A_{HR} = 50925.571 \cdot ft^2$ $\quad$ $A_{DR} = 13694.986 \cdot ft^2$

$A_{TA} = 77862.565 \cdot ft^2$ $\quad$ $A_{HA} = 56751.453 \cdot ft^2$ $\quad$ $A_{DA} = 21111.111 \cdot ft^2$

WEIGHT BALANCE:

$W_{FL} = 8287.388 \cdot \text{lton}$ $\quad$ $W_T = 8359.5 \cdot \text{lton}$ $\quad$ $ERR_{WEIGHT} = -0.008626$

$W_1 = 2736.993 \cdot \text{lton}$ $\quad$ $W_5 = 862.05 \cdot \text{lton}$ $\quad$ $W_{LS} = 5973.922 \cdot \text{lton}$

$W_2 = 576.394 \cdot \text{lton}$ $\quad$ $W_6 = 462.912 \cdot \text{lton}$ $\quad$ $W_P = 668.3 \cdot \text{lton}$

$W_3 = 339.26 \cdot \text{lton}$ $\quad$ $W_7 = 117.37 \cdot \text{lton}$ $\quad$ $W_{F41} = 2053.939 \cdot \text{lton}$

$W_4 = 335.859 \cdot \text{lton}$

STABILITY/PAYLOAD:

$C_{GMB} = 0.204$ **(.09 - .122)** $\quad$ $F_P := \frac{W_P}{W_{FL}} \cdot 100$ $\quad$ $F_P = 8.0641$

APPENDIX G. INTEGRATED SHIP DESIGN SYSTEM USER'S GUIDE

INTEGRATED SHIP DESIGN SYSTEM USER'S GUIDE

1. Computer System Requirements.

The ISDS was developed using the following software products;

- Microsoft Excel, Version 7.0 for Windows 95 for the Payload Spreadsheet.
- Mathcad 7 Professional for Windows 95 for the MIT Math Model and the MathConnex working environment.
- Matlab 5 with the Optimization Toolbox for the Numerical Optimizer.

2. Getting Started.

First and foremost it is strongly encouraged that the user become familiar with the mechanics of the application programs and the supporting documentation for the MIT Math Model prior to using ISDS.

2.1. Open ISDS in MathConnex. The worksheet will display the block and wire diagram of the ISDS, and by following the arrows you can step through the program logic path that connects the different application modules. The two view boxes display the intermediate results from the optimizer and the final design summary.

2.2. Open the file "outopt" in the Matlab editor/debugger. This file contains the diary output of the optimizer that is normally displayed in the Matlab command screen. When using MathConnex, the Matlab command screen is not viewed, so this permits the optimization details to be stored for later viewing and reviewing.

2.3. Each time the ISDS is run, "outopt" is updated and its contents should be viewed by the user to ensure the optimizer is producing feasible results.

2.4. To de-clutter the file after each session, "outopt" can be cleared by selecting all in the edit menu and then deleting.

3. Modify Payload Spreadsheet.

3.1 Double-click on the Excel icon to activate the Payload spreadsheet for editing.

3.2 Delete the contents of the cells of the combat systems that will NOT be installed in the design. Remember only to delete the cells with numerical values, not the system name, so that the data can be reloaded for different designs later on.

3.3 A complete Payload spreadsheet is included in the ISDS program files under the heading "mit_payload". By using the cut and paste command, data can be easily reloaded into the MathConnex Excel spreadsheet from "mit_payload".

3.4 Selected payload values are then loaded into the global variable "Payload" for

transfer to the Initial Values and Final Design Synthesis Mathcad worksheets.

4. Modify the Initial Values Mathcad Worksheet.

4.1 Double-click on the Initial Values Mathcad icon to open the Mathcad worksheet.
4.2 Inspect and modify, as required, the yellow highlighted sections. Cross-check highlighted values between Initial Values and Final Design Synthesis modules to ensure consistency between the two.
4.3 Three arrays are output from this module;

- The design variable independent weights and center of gravity data are output as "out0". This has a change variable name in Matlab to "w".
- The first guess at the design variable values for beam, draft and waterline length are output as "out1".
- Additional design specifics that need to be passed to the Matlab optimizer and The Final Design Synthesis Mathcad module are output as "out2". This has a change of variable name in Matlab to "z".

5. Modify the Matlab Optimizer Worksheet.

5.1 Double-click on the Matlab icon to activate the Matlab worksheet.
5.2 This Matlab worksheet contains the variables that control the optimization process. There are two choices for assigning the initial guess of the design variables, "x0". The first uses the guess generated by the Initial Values Mathcad worksheet, and the second can be manually input by the designer. To switch between the two, place a "%" in front of the line you want to inactivate and delete the "%" on the line you want to activate. Make sure you click the "check" button on the toolbar to save the change to the Matlab worksheet.
5.3 The side constraints of the design variables, vlb and vub, can be modified to ensure a global vice local minimum is being sought. Only the first three bounds should be modified, as the last two are constrained to keep the Math Model valid when using the Taylor Standard Series. Make sure you click the "check" button on the toolbar to save the change to the Matlab worksheet.

6. Cross-Check the Final Design Synthesis Mathcad Worksheet.

6.1 Make sure all the yellow highlighted sections match between the Initial Values and the Final Design Synthesis worksheets.

7. Interpreting Results.

7.1 Results are displayed in two view boxes within the ISDS MathConnex

worksheet. The first view box contains the output from the Matlab optimizer. Additional optimization details are contained in the "outopt" file in the Matlab editor/debugger.

7.2 The second view box contains a summary of the Final Synthesis Design Mathcad worksheet. The Design Checks column should be scrutinized by the designer to ensure that the installed power plant is sufficient and that the area weight errors are reasonable.

7.3 If the area error is excessive, it can be adjusted by the designer to bring it into compliance. The deckhouse volume (V_D) is the variable that is modified to adjust this error. In the Area/Volume Balance section of the Summary page in the Final Design Synthesis Mathcad worksheet there is a range for the value of V_D. The model can be set up so that the value is calculated using the equation for V_{DMIN} or V_{DMAX} or any numerical value can be chosen between V_{DMIN} and V_{DMAX} and assigned as the value of V_D in the worksheet. The Matlab function M-file "cubicnum_calc" must also be modified so that the value of V_D is consistently calculated. Change the value and run the ISDS again and check the area error, if it is still unreasonable, adjust V_D up or down within the range until it reaches a reasonable error.

7.4 The entire detailed design can be reviewed by double-clicking on the Final Design Synthesis Mathcad icon.

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